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INTRODUCTION TO  
SOIL SCIENCE

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G. W. LEEPER







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# INTRODUCTION TO SOIL SCIENCE

by

G. W. LEEPER, M.Sc. (Melb.)

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## PREFACE

THE MAIN PURPOSE OF THIS BOOK IS TO GIVE A SHORT ACCOUNT OF SOIL SCIENCE as it exists in the middle of the twentieth century. The great developments in this subject during the last thirty years have as yet failed to spread to the more popular text-books. I know of only one book in the English language which succeeds in what I am attempting to do here—Comber's *Introduction to the Scientific Study of the Soil* (the latest edition of which is incorporated into a larger book, *An Introduction to Agricultural Chemistry*). Admirable as it is, Comber's book is written for English readers, and in Australia it suffers some of the disadvantages of a book on nature study written about the English countryside. Any account of natural science must quote examples close to home or it will fail to give the reader a feeling of reality. This book is written for Australians. I have taken most examples from Victoria, since I have had the Victorian reader most in mind. In many places, however, I have suggested where examples in other States may be found.

I have included a map and description of the soils of Victoria.<sup>1</sup> Prescott's *Soils of Australia* (C.S.I.R. *Bulletin* 52 (1931), supplemented in 1944 by *Bulletin* 177) covers the whole of Australia. His bulletins are written for more advanced readers than this book is, and the map here published for the first time differs from Prescott's in some ways, mostly in the degree of detail in the south. It must be emphasized that the map is highly generalized and provisional, and will need several changes before it can be regarded as satisfactory. In spite of its faults, it is important that a map based on modern ideas should be published and that the old-fashioned classification of soils as "volcanic", "sedimentary", and so on, should disappear from our teaching. While I have drawn on various sources for this map, any responsibility for mistakes is my own.

The map serves to emphasize the natural chemical poverty of most of the better-watered regions of Victoria. Too many people still imagine that the Western District is highly fertile. In fact its areas of really rich soil are small, and the improvement of its extensive poor areas is an achievement that should be better known.

This book is concerned with science and not with lore. A vast amount of traditional teaching has accumulated around the arts of farming and gardening.

<sup>1</sup> Howell's *Soil Problems in Wheat Growing* (1911) contains some analyses of Victorian soils, but no map. The *Report of the Victorian Regional Boundaries Committee* (1945) includes a map of Victorian soils which has some features in common with my map—notably, the great eastern area where our ignorance is covered with the term "mountainous".



This is not the place for such instructions; rather, a book on the science of soil provides a background of knowledge and ideas with which the gardener's lore can be both understood and judged. Further, many garden soils are made up, wholly or in part, from imported material, while this book deals with soils that have formed naturally in their present position.

I am grateful to my colleagues who have read the manuscript and given suggestions, especially to Dr. E. G. Hallsworth, Dr. R. J. Best, Dr. T. J. Marshall, Professor J. S. Turner, Professor S. M. Wadham, Dr. H. L. Jensen, and Mr. F. Penman. Messrs F. Penman and J. K. Skene have kindly provided hitherto unpublished information from the records of the Victorian Department of Agriculture which appears on pp. 29, 34, and 96.

I would also like to thank the technical staff of the School of Agriculture for their help, especially Mr. H. R. Arthur, who drew the maps and diagrams.

The book is designed for any reader who understands chemical terms. I have particularly had in mind the needs of the teacher in general science.

G. W. L.



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PART I

MAPPING, CLASSIFICATION  
AND FORMATION OF SOILS







## CHAPTER I

### PROFILES AND MAPS

#### DESCRIPTION OF A PROFILE

THE PROPER INTRODUCTION TO THE STUDY OF SOIL IS NOT IN THE LABORATORY but in the field. We can observe the loose layer of a ploughed paddock (see p. 65), or the relation of soils to the growth of crops or native plants, or we can start with the face or exposure which we see in a vertical cut by the side of a road, in a quarry, or in a trench. Such an exposure is called a *profile*.

A soil profile is normally examined to a depth of four to six feet. While our interest is usually concentrated on the four to six inches of top soil which lies directly under our control, most plants send their roots three or more feet below the surface. An account of any soil, in order to be adequate, must therefore include the nature of the subsoil.

Starting from the surface, the observer notes the colour and consistency of the soil and the pattern of the cracks. He breaks off a sample from the face, crushes it and works it with water in his hand until all lumps are broken and the mixture is moist without being sticky. He estimates the "texture" of the sample from its feel between the fingers and thumb and palm of the hand, and places it accordingly in one of a dozen classes—viz., sand, loam, clay, and intermediate classes, as set out in Table I. These classes as used in soil surveys correspond fairly well to the farmer's terms. "Loam", however, does not imply the richness in humus which gardeners attach to the word. We can reproduce each texture from No. 2 to No. 6 by making up mixtures of pure sand and a tough clay in varying proportions; as the proportion of clay increases, the mixture feels increasingly tougher or "heavier". The terms "light" and "heavy" represent the sandy and clayey ends of the series. They have nothing to do with specific gravity—a cubic foot of clay weighs less than a cubic foot of sand—but they refer to the ease or difficulty of digging or cultivating sand or clay.

TABLE I

#### TEXTURES IN INCREASING ORDER OF HEAVINESS

1. *Sand*—Does not cohere, and is coarse to the touch.
2. *Loamy sand*—Cohesion just perceptible; a cast can just bear handling.
3. *Sandy loam*—Coheres, yet is easily friable; individual sand grains can be felt.
4. *Loam*—Both friable and coherent; sand grains cannot be felt in a moist sample.
5. *Sandy clay loam*—Like a clay loam, but sand grains can be felt.
6. *Clay loam*—Somewhat friable, but also somewhat plastic; rolls out to a ribbon while a loam breaks up.
7. *Sandy clay*—Like a clay, but sand grains can be felt.
8. *Clay*—Tough and plastic.



The above list refers to the texture after any gravel or stone has been set aside. This may have to be included in the description (e.g., *gravelly loam*). Certain soils with a peculiarly smooth feel when moist are called *silty*—e.g., *silty loam*, *silty clay loam*. Clay is sometimes subdivided into *light*, *medium*, and *heavy*; further, some clays are noted as being friable and crumbly in spite of their toughness, but most clays are not friable, and they are assumed not to be unless so stated.

As we follow the profile downward we look for any change in appearance or texture. A change in texture is usually associated with a change in colour, in the pattern of the cracks, or in the frequency of roots; or it may sometimes be picked out by a different degree of resistance to jabs with a knife. Each layer of soil that is separated from its neighbours in this way is known as a *horizon*. We may eventually get a description like this:

Horizon 1 (0-8 inches)	Grey loam <sup>1</sup> , rather silty.
Horizon 2 (8-13 inches)	Light grey loam, structureless (i.e. no natural large lumps or aggregates or cracks).
Horizon 3 (13-15 inches)	Becoming heavier in texture and whitish grey, with large concretions of ironstone, and cemented flakes of rock up to 1 inch long.
Horizon 4 (15-26 inches)	Yellowish grey clay with very few roots showing.
Horizon 5 (26-44 inches)	Yellowish grey clay with red and grey mottling, with a few lumps of rock.

This is a field description of the profile shown in Plate I.

If a soil is to be analysed, representative samples are taken from each natural horizon; the old method of sampling to six inches, then taking the next six inches and so on, without regard to horizons, is now abandoned, except for a few studies, in particular when the amount of water or soluble salt is to be measured.

It is best to study profiles in pits freshly dug for the purpose. If a roadside cutting is used, it must of course be first trimmed with a spade so as to expose a fresh surface. However, ready-made exposures are often not available, and digging a new pit is laborious, so the usual method is to dig to the desired depth with a 3-inch or 4-inch post-hole auger, or a screw auger if the soil is not too dry. These augers normally reach a depth of 3 ft. 6 in.; an extension is sometimes added to enable them to reach to 6 ft. 6 in. This method gives the colour and texture of each horizon, but does not reveal the presence or absence of well-marked patterns of cracks, which may be vitally important in drainage and which can be easily seen in a pit.

Profiles are sometimes studied to a greater depth than the 6 ft. 6 in. just mentioned, though there would need to be a special reason for such a time-

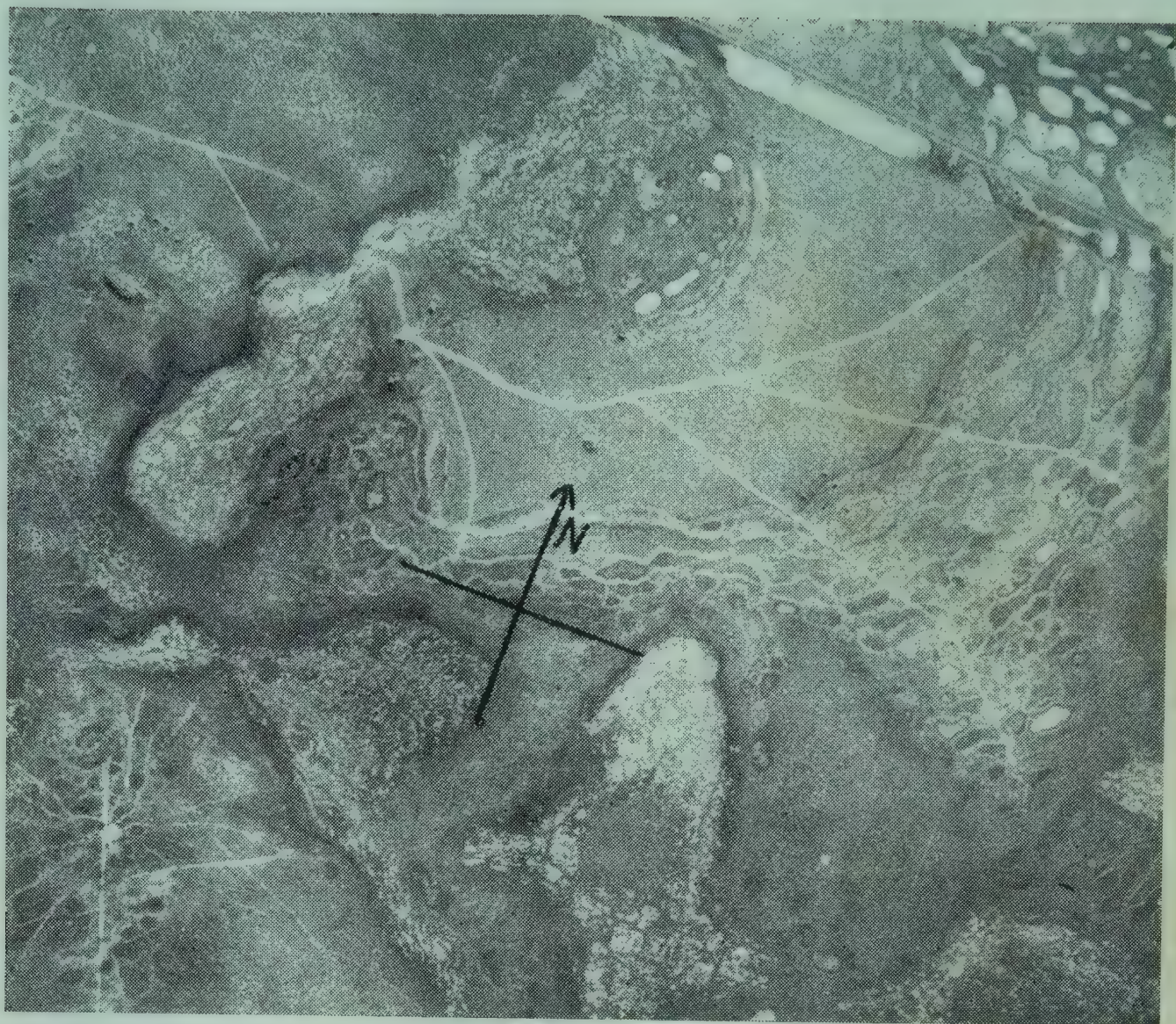
<sup>1</sup> Both here and in the succeeding discussion of profiles there is little direct reference to "humus", or organic matter. This is rarely a major constituent of soil, and while it may confer a dark shade, its relation to the colour of the soil is very rough (see p. 56).





*Plate I.* Profile of Hallam loam. Note white structureless sub-surface, ironstone band, and crumbly pattern of the clay subsoil (Photo, B. A. Pearl).







consuming task. This may be done in irrigated country in order to find whether a freely-draining layer occurs in the next few feet. We may also get valuable information from a study of the deep subsoil where the land is used for growing trees. In equatorial climates especially (e.g. New Guinea), trees may obtain many of their necessary nutrients from decomposing rock at as great a depth as twenty feet. In temperate climates, one example occurs in the pine plantation at Mt. Burr (just west of the border of Victoria and South Australia), where roots that have grown down twenty feet through cracks in the limestone have reached the underlying rich layer of volcanic tuff.

When examining any profile, one also notes what kind of tree or other vegetation grows near by. Since every plant has its own range of physical and chemical requirements, the fact that a certain tree grows naturally on a soil provides some evidence about that soil, though only a few plants are really good indicators. Bracken denotes good drainage and a fair rainfall; rushes denote a wet subsoil; succulent salt-tolerant plants, including samphire, indicate high salinity. In every district one can recognize certain weeds that are generally related to high or low fertility. Thus the fly-catching sundews grow on land that is chemically poor, while some thistles—e.g. variegated thistle—denote high fertility. Bracken and thistles grow much taller on good than on poor land, though the height of thistles varies greatly with the season; and so on. All these general rules call for a good deal of judgment in their use. Thus, sorrel is commonly spoken of as a reliable indicator of acidity. While it tolerates high acidity, however, it grows under a wide range of conditions and need not indicate anything in particular.

When we observe a profile such as the one just described, a number of questions immediately arise. *How did it get like that?* Why that ironstone above the clay? Why the mottling of red and yellow, why the sudden transition from loam to clay? In a later chapter we will deal with the question, How did it get

---

*Plate II.* Aerial photograph and Soil map of country near Mt. Gellibrand, Western District, Victoria. (Photo, R.A.A.F.)

Most of the boundaries of the soil map were copied directly from the photograph. This is wool-growing country in the nearer Western District, and is mostly covered with native grasses. Parent rock basalt, also some volcanic tuff.

White areas in soil map: Grenville loam, grey loam overlying heavy clay, calcareous at 30 inches.

Diagonal shading, full or broken lines: Heavier surface than Grenville loam, otherwise similar. Periodically waterlogged in winter (note drains ploughed through this area). Poorer growth in October (time of photograph) than the slopes above.

Cross-hatched: Mooleric clay, black friable clay of higher fertility than other types (p. 29), often carrying thistles.

Black check: Rock on surface, with brown loam between rocks, of high fertility but shallow. These are the tops of "stony rises" of chaotic distribution which prevent a natural drainage system.

(Soil Survey of Mt. Gellibrand, *Proc. Roy. Soc. Vic.* 49, 77-134.)



like that? For immediate purposes, however, we are concerned simply with observing and recording the fact that at a particular point on the map there was found fifteen inches of grey loam overlying at least three feet of yellowish grey clay.

### THE SOIL TYPE

Exploring the countryside in the neighbourhood of the spot just sampled, we are almost sure to find some places where the profile is similar to that just described. The transition from loam to clay may be at 13 inches in one place and 17 in another, but such differences are unimportant and it is essentially the same soil with the same general appearance. In this way we arrive at the concept of the *soil type*,<sup>2</sup> which was developed in U.S.A. and has been adopted in Australia, New Zealand and a few other countries. Each type is given a double name—a place-name, followed by the texture of the surface soil. Thus, the type described in the preceding section is *Hallam loam*. Such a name of course tells us no more than the surface texture and the locality where it was first described. One might suggest that we might as well use a catalogue number such as V376/21, with an index system likewise arranged to allow any reader to look up the original description. However, the name can be more easily used in print and discussion than the number.

A soil type is analogous to a species in biology, but unlike a species it does not extend beyond the boundaries of a nation—in Australia, it seldom extends into two states. Closely similar types in different states will in the course of time be correlated with each other, but they will probably keep their different names.

### CRITERIA FOR TYPES

A question now arises; suppose some holes show a transition from loam to clay, not between 13 and 17 inches, but between 4 and 8; is this shallower soil to be made a separate type from the first?

Soil surveying is essentially practical. The type is a mapping unit. We separate one type from another if we know that some plants grow differently on the two soils, or if we believe that differences in plant growth are likely to develop between them. In the case just mentioned, we would classify and map the soils differently if there were an important area of the shallower one. Roots usually concentrate in the upper horizons when the subsoil is impermeable, and a plant with the bulk of its roots in the upper 6 inches will make different growth from one with its roots distributed through the upper 15 inches. Sometimes a patch of soil which is similar to the main type but has some

<sup>2</sup> Owing to this special use of the word *type* in soil science, we cannot also use it in its ordinary English meaning. Two related, but not identical, profiles can be said to be of the same *kind*, but not of the same *type*.



minor difference is mapped as a *phase* of that type; an expanse of Hallam loam where the clay was not reached until at least 24 inches might be mapped as "Hallam loam, deep phase".

In the irrigation districts, where most of our detailed surveys have been made, ease of drainage is the most important feature for distinguishing types. This may be seen in Table 2, which compares four types from an irrigated area of country typical of the Victorian Mallee where sand-ridges alternate with flats. The first type, Murray sand, is found on the highest levels of the ridge. The other three types commonly occur in succession on passing down the ridge towards the flat, Barmera sand and Barmera sandy loam<sup>3</sup> being found on the upper slopes and Coomealla sandy loam below them, with still other types on the flat itself. All these types have some features in common (see p. 26) but we are concerned here with their differences, which reside in their texture.

TABLE 2  
TEXTURES OF FOUR SOIL TYPES IN THE FIRST SIX FEET

	Murray sand	Barmera sand	Barmera sandy loam	Coomealla sandy loam
0-1 ft.	Sand	Sand	Sandy loam	Sandy loam
1-2 ft.	Sand	Sand	Sandy loam	Loam
2-3 ft.	Sandy loam	Sandy loam	Sandy clay loam	Sandy clay loam
3-4 ft.	Sandy loam	Sandy loam	Sandy clay loam	Clay loam
4-5 ft.	Sandy loam	Sandy clay loam	Sandy clay loam	Light clay
5-6 ft.	Sandy loam	Sandy clay	Sandy clay	Medium clay

(Each texture is the average over the foot for which it is quoted.)

Murray sand is highly permeable; no horizon has a texture heavier than sandy loam. Moreover, sand continues for many feet in the subsoil, so that there is little risk of waterlogging under irrigation. This type is preferred for oranges along the Murray Valley.

Barmera sand resembles Murray sand in the upper four feet, but is less permeable at the lower levels—a fact which incidentally shows the need for exploring below the upper three or four feet. Barmera sandy loam is one degree heavier than Barmera sand (cf. Table 1) in the top four feet. Oranges are risky on the Barmera types, though they may succeed if drains are laid.

<sup>3</sup> Since it takes two components to name a type (place-name and texture) the same place-name is sometimes given to two associated types, as here. This scheme is economical of names, but otherwise has no great merit; it seems to be going out of fashion in America. Such a combination is called a *series*—e.g., the Barmera series.



Coomealla sandy loam differs markedly from the other types in the deep subsoil, which can hold up the movement of water and may cause waterlogging after a heavy irrigation. Vines are the standard crop on soils of this nature, which are common along the Murray.

#### THE SOIL MAP AND ITS USE

The soil surveyor observes the profile at regular intervals over the country, digging one hole in every five acres for irrigated land, where detail is needed, and in every twenty acres (or more) for less detailed work. He uses this information to draw his map of soil types (Figs. 1, 2). The exact boundaries between types can often be observed while walking over the land, either by a change in the surface soil or by a change in vegetation, or perhaps by noting the subsoil turned up near a fence-post. Aerial photographs are very useful in defining the boundaries, especially where native vegetation still exists (see Plate II and *Journal*, C.S.I.R., Vol. 3, p. 229 for examples).

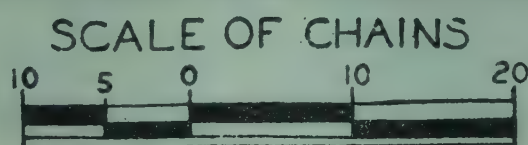
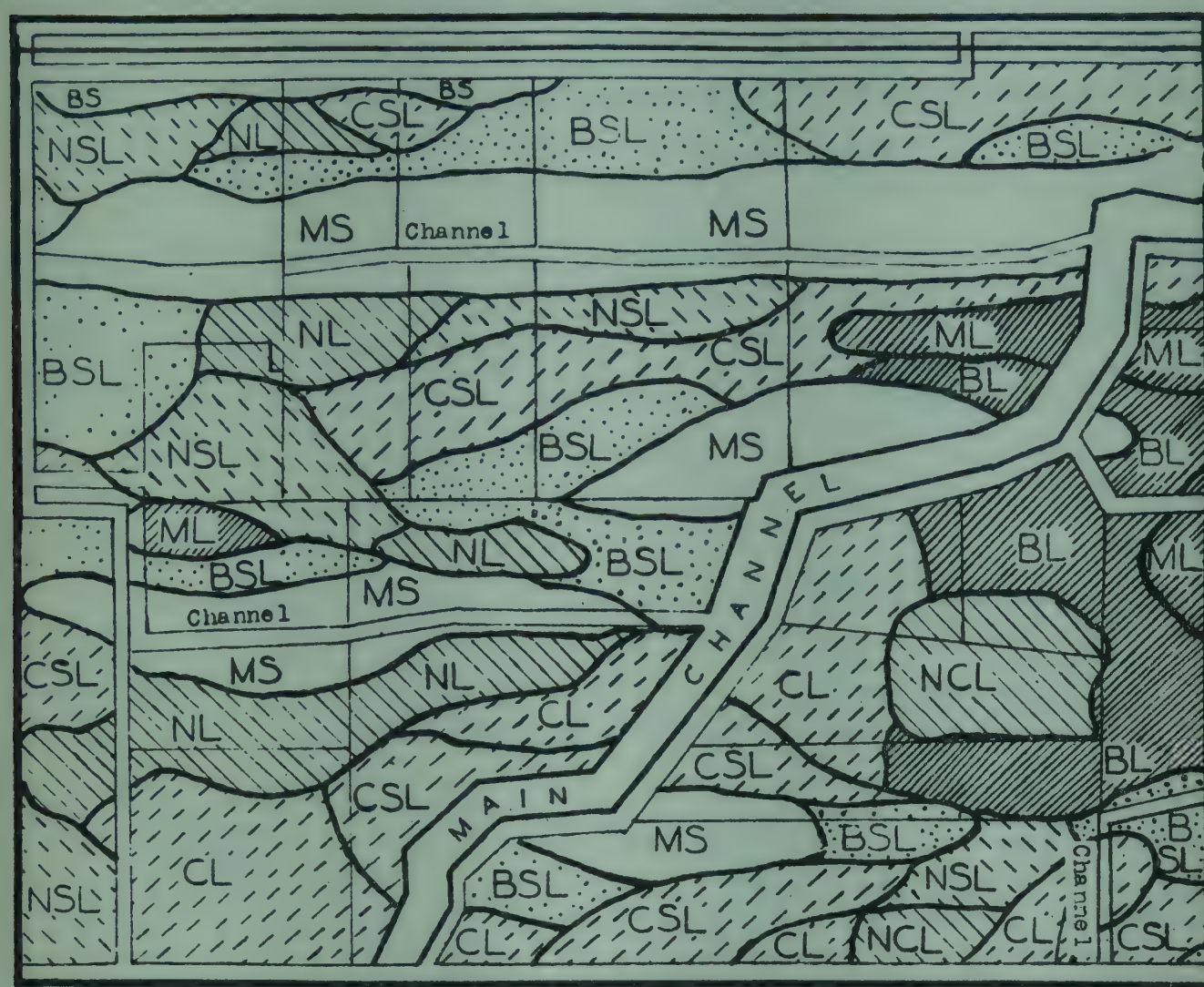
A soil map is an essential piece of information about any country. It should be used in deciding whether or not to settle a new district, whether to irrigate a dry district and how to lay out its channels, or where to try a new crop. As soon as we have gathered information about the growth of crops on any one type, we can apply that information to the same type in another district. Murray sand has virtues and problems of its own, wherever it occurs; if a deficiency or a disease is successfully treated on one area of Murray sand, that treatment will probably succeed in another area. Thus, the more information is collected, the more useful does the map become. This statement applies particularly to the United States of America, where the making and the use of soil maps are far in advance of Australia. Soil maps have played an essential part in many national undertakings, such as determining suitable trees and sites for shelterbelt planting, re-planning farms to guard against soil erosion, or changing to new forms of production. An excellent example of the application of an

---

Murray sand.	..	No horizon heavier than sandy loam. Tops of ridges. Murray Pine and hopbush.
Barmera sandy loam.	..	Light clay at 5 feet or deeper. Upper slopes and sandy rises. Sandalwood and belar.
Coomealla sandy loam.	..	Clay loam in fourth foot, light clay at 4 ft. 4 in. On gentle slopes. Mallee with belar.
Coomealla loam.	...	Clay loam in third foot, light clay at 3 ft. Otherwise as above.
Nookamka sandy loam.	..	Light clay at 3 ft. 6 in. In depressions. Belar.
Nookamka loam.	..	Light clay at 2 ft.
Nookamka clay loam.	..	Light clay at 1 ft. 6 in.
Merbein loam.	..	Clay loam in second foot, light clay at two feet. Low-lying.
Benetook loam.	..	Similar texture to Merbein loam. Mallee and bluebush.
Contours are omitted for simplicity. The ridges of Murray sand mostly exceed 180 feet, the depressions of Nookamka loam are mostly below 165 feet.		



# SOIL MAP OF MERBEIN









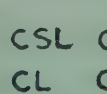


	MS MURRAY SAND		NSL NOOKAMKA SANDY LOAM
	BSL BARMERA SANDY LOAM		NL NOOKAMKA LOAM
	CSL COOMEALLA SANDY LOAM		NCL NOOKAMKA CLAY LOAM
	CL COOMEALLA LOAM		ML MERBEIN LOAM
			BL BENETOOK LOAM

Fig. 1. Soil map of irrigated country near town of Merbein (C.S.I.R. Bulletin 123). The list opposite gives the most important relations of textures to depths, together with observations of original plant cover.

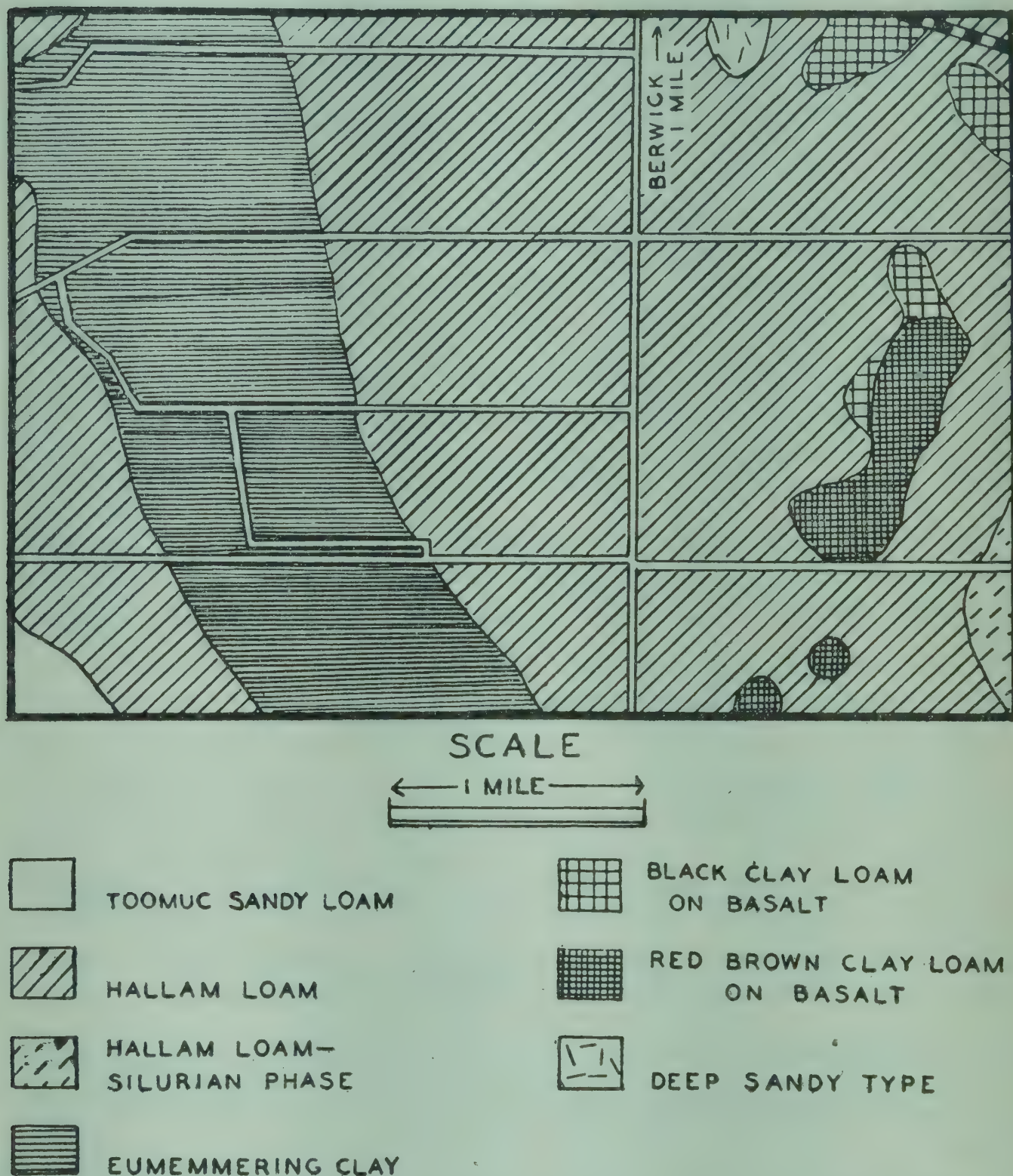
Australian map occurred when an urgent need arose to expand the acreage of rice, which was established on the Murrumbidgee Irrigation Area in 1924. Rice demands a soil that holds water strongly; fortunately, a large area of suitable soil was found in the Wakool district (in the Riverina) which had been mapped in 1941, and 3,000 acres of rice were cropped there in 1944.



Progressive farmers in the irrigated districts of Victoria and on the Murrumbidgee have learned to discuss their own soils by their systematic names, which is an encouraging sign.

American agriculturists have worked out schemes for arranging soil types

## SOIL MAP, BERWICK DISTRICT



*Fig. 2.* Map of country near Berwick, Vic. An unusually simple area, in which soil types correspond with geological types, viz. basalt (black and red-brown types); Silurian rock (Hallam loam), swamp (Eumemmering clay), and Tertiary sand (Toomuc sandy loam consisting of two feet or more of sandy loam or sand overlying yellow clay; also a deep sandy type of small extent). The Silurian phase of Hallam loam has the parent rock within four feet of the surface. This and the basaltic types occupy the higher land. The other types are described in the text.



in order of productivity. There are two main ways of doing this; the first is to give marks for physical properties (full marks for loam and lower marks for clay and sand), chemical fertility, degree of slope, proneness to erosion, and so on. The other method is to collect figures for the yield of crops which farmers obtain from each type. Thus, Table 3 compares<sup>4</sup> two soil types, Honeoye silt loam and Wooster gravelly loam. The former is more productive in general, but the latter is better for potatoes, which require a loose surface soil. The figures refer to the yield for each crop obtained on that soil type as a percentage of that obtained from first-class land. The first figure gives the yield on the unfertilized land, the figure in parenthesis the yield after fertilizing. Thus, no amount of fertilizing will bring Wooster up to the fertilized Honeoye for maize or oats, or Honeoye up to Wooster for potatoes. The last two columns give the order of merit, from best (I) to worst (10) in which the particular type falls, the first column giving the order of inherent productivity and the second column the order of productivity if fertilized.

TABLE 3  
RATING OF TWO SOIL TYPES

Soil Type	Productivity Index for				Grade	
	Maize	Oats	Pasture	Potatoes	I	II
Honeoye silt loam ..	70 (100)	80 (100)	90	50 (60)	3	1
Wooster gravelly loam	50 (70)	50 (80)	50	70 (90)	5	3

#### SOIL SURVEYS IN AUSTRALIA

Table 4 shows the areas of soil surveys carried out in Australia up to 1947, whether published in printed form or not. The bulk of the surveying in the eastern States has been done by the Council for Scientific and Industrial Research. This was first concentrated on the closely settled country commanded by irrigation water from the Murray and tributaries, and most of this irrigated land has now been covered. Later surveys were made of areas associated with special problems, including stock diseases and soil erosion. In Western Australia the Department of Agriculture has surveyed large areas of actual or possible wheat-growing country.

The soil surveys published in Victoria up to 1947 total 660 square miles out of the state's 88,000; including still incomplete work, the total is over 1,000 square miles. As compared with this, many states in America have published surveys of at least half of their area at a scale of one inch or more to

<sup>4</sup> Extracted from *Soils and Men*, pp. 1014-5.



TABLE 4  
SOIL SURVEYS OF AUSTRALIA  
*Published or available for Inspection (1947)*

State	Detailed (1000 acres)		Reconnaissance (1000 acres)	Institution Responsible
	Irrigated	Unirrigated		
New South Wales	736	12	803	C.S.I.R. only
Victoria ..	367	182	150	C.S.I.R.; Vic. Dep. Ag.; Melb. Univ.
South Australia	87	972	2,480	C.S.I.R., one by S.A. Dep. Ag.
Tasmania ..	—	230	487	C.S.I.R. only
Western Australia	—	1,492	(5,000)*	W.A. Dep. Ag., also C.S.I.R. and W.A. Dep. Forests
Queensland ..	3	5	—	Q. Dep. Ag.
Australia ..	1,193	2,893	(9,000)	

\*On a very rough scale.

the mile. The Australian cost of surveying and mapping a large area, including aerial photographs and all laboratory work, is 2d. to 3d. an acre for a detailed map, and 1d. an acre for reconnaissance. The most detailed work in horticultural districts has cost 1s. an acre.

Nos. 1, 2, 5, 6 and 8 of Table 5 are irrigated fruit-growing areas, nos. 3 and 4 consist of irrigated pasture, and the last three surveys are in southern Victoria, on non-irrigated land.

These publications normally include laboratory analyses of soils, and some discussions of the problems and difficulties attached to individual types. Some surveys also contain an account of land utilization, especially numbers 10 and 11 in Table 5.

#### GROUPING SOIL TYPES IN MAPPING

##### 1. *The Soil Complex*

The amount of detail that can be shown must depend on the scale. Even at four inches to the mile one would not map a strip less than 50 yards wide ( $\frac{1}{8}$  inch on the map). On the two-inch scale, which is the largest scale used except for intensive horticulture, the practical limit comes at a strip of 100 yards across. Now in many districts one finds transitions from one type to another



and back again in the course of fifty yards. Sometimes the change is very striking. On the red plains to the west and north-west of Melbourne, small patches of black soil occur which may be only a few yards in diameter. This black type differs greatly from the surrounding red, being much more friable and more fertile, and even producing twice as much vegetative growth in some seasons at Werribee. Since it is impossible to map such details, we either omit the type of smaller extent or mark the whole area as a "complex". In the wheat lands of the Wimmera some paddocks consist of contrasting red and grey soils so closely interwoven that they must be mapped as a complex. Here and elsewhere the red type commonly occurs on the higher ground.

TABLE 5  
PUBLISHED SOIL SURVEYS OF VICTORIA (1947)

Locality	Scale inches per mile	Area acres	Published Date	Where Published
C.S.I.R. with Vic. Dept. of Agriculture				
1. Swan Hill—				
Woorinen ..	4	5,000	1930	C.S.I.R. <i>Bull.</i> 45
Murrabit ..	4	1,000	1932	J. C.S.I.R. 1932
Tresco, Nyah	4	9,300	1933	C.S.I.R. <i>Bull.</i> 73
2. Mildura—				
Merbein ..	4	8,000	1939	C.S.I.R. <i>Bull.</i> 123
Mildura ..	4	17,000	1940	C.S.I.R. <i>Bull.</i> 133
Red Cliffs ..	4	12,000	1941	C.S.I.R. <i>Bull.</i> 137
3. Kerang .. ..	2	54,000	1939	C.S.I.R. <i>Bull.</i> 125
4. Moira .. ..	2	197,000	1942	C.S.I.R. <i>Bull.</i> 152
Victorian Department of Agriculture				
5. Bamawm ..	2	900	1936	J. Dept. Agric. Vic. 1936
6. Tatura Farm ..	9	100	1936	<i>ib.</i>
7. Myrtleford Tobacco Farm	16	39	1941	<i>ib.</i> , 1941
8. Shepparton ..	8	18,000	1944	State Labs., Soil Sect., <i>Tech.Bul.</i> 3
School of Agriculture, Univ. of Melbourne				
9. Mt. Gellibrand ..	2	12,000	1936	<i>Proc. Roy. Soc.</i> Vic., vol. 49
10. Berwick ..	2	40,000	1940	<i>ib.</i> , vol. 52
11. Kooweerup ..	$\frac{1}{2}$	50,000	1942	<i>ib.</i> , vol. 53



## 2. *The Association*

When we come to map larger regions, using a scale of four or eight miles to the inch, a similar problem arises. Some of the detail of the smaller map must be sacrificed. At this point the term *association*<sup>5</sup> is useful. This means the sequence of types found in many kinds of undulating country. In the simplest case, one type occurs on every hill-top, another on every slope, and a third (usually the heaviest) on every flat; we call the whole collection from hilltop to hilltop an *association* (Fig. 3). An area of as much as 20 or 30 square miles can thus be mapped as one *association*.



Fig. 3. Association of four soil types with vertical scale exaggerated.

## 3. *The State-wide Map*

Neither *Hallam loam* nor *Merbein association* conveys anything to the reader who has not studied the detailed descriptions of local types. Is it possible to go further and describe soils by a relatively small number of general names, so that each name will be used and recognized throughout the world, not only by specialists but also by people who have some general agricultural knowledge? This involves classifying soils according to their nature—that is, on what is called a *taxonomic* basis, as contrasted with the grouping of neighbours as a complex or an association as has just been described—that is, on a *geographic* basis. The next chapter deals with this problem.

<sup>5</sup> Another word, *catena*, (the Latin for *chain*), has sometimes been used in the same sense, but many writers have come to use it for an association in which the parent material is known to be the same throughout. The word is therefore of little or no value as a mapping term.



## CHAPTER II

### THE CLASSIFICATION OF SOIL TYPES

#### CRITERIA

HOW SHOULD THE WORLD'S SOIL TYPES BE CLASSIFIED? WE MIGHT USE THE texture of the surface soil, which is for some purposes the most useful feature for classifying. Other less useful methods—such as the nature of the parent rock—have now lost favour. We will use here the principle which is now generally adopted by soil scientists, though its details are still far from settled. Modern classification depends on the nature of the whole profile, and not on the surface alone. The major properties looked for are as follows (not necessarily in order of importance):

1. Presence or absence of free lime<sup>1</sup>, either as white streaks or as large round concretions.
2. Colour.
3. Degree of contrast in texture of successive horizons, and sharpness of transition.
4. Degree of acidity or alkalinity.
5. Depth to parent rock.
6. Presence or absence of ironstone gravel.

All of these can be observed directly except the acidity or alkalinity, and this can be measured quickly by means of indicators (for method see p. 199). The pH's of soils range from 4 to 10; anything from 8 upwards is definitely alkaline, from 6 downwards is definitely acid<sup>2</sup>. It may seem strange at first that the scientist should use colour in classifying. Some people have over-emphasized colour; but it is associated with other important features and is not accidental. Other properties may less frequently be used in classifying. Gypsum crystals in the subsoil may be used; high salinity is sometimes used, though this cannot usually be observed without analysis. Structure may also be referred to (p. 65). The amount of organic matter ("humus") is not useful for classifying unless a great deal is present (see *peat*, p. 31).

In comparing numbers of profiles with one another it is often convenient to use models in which the soil is glued to strips of three-ply and the vertical scale reduced to one quarter (see p. 205 and Pl. III).

<sup>1</sup> "Lime" in general can mean  $\text{CaO}$ ,  $\text{Ca(OH)}_2$ , or  $\text{CaCO}_3$ . The first two cannot persist in soil since  $\text{CO}_2$  is always present. "Free Lime" therefore means  $\text{CaCO}_3$  and includes the small amount of  $\text{MgCO}_3$  which always accompanies it. The "popular" use of lime to mean calcium has, of course, no place in this book.

<sup>2</sup> The pH of a soil denotes that of a suspension with a weight of water equal or double that of the solid. The term *acid* should not create alarm. Many acidic soils grow good crops. The nature of acidity will be dealt with later; meanwhile it may be regarded as an important property, usually though not always connected with chemical poverty, especially in Ca and Mg and K.



## TWO CONTRASTING TYPES—PODZOL AND MALLEE

To introduce the system, consider two soil types which have already been mentioned—Hallam loam, and Barmera sandy loam. Both types have a relatively light surface and a relatively heavy subsoil, but there the resemblance ends. They differ in all but the fifth of the six properties in the above list.

(1) The outstanding properties of Hallam loam are: no lime in the profile, definitely acid throughout (pH 5.0 to 5.5); a grey surface of fairly light texture overlying a yellow clay with a sudden transition from the one to the other; and ironstone gravel just above the clay (this last feature, though usual, is not an invariable one with this type). These properties are common to a great many types in the wetter regions of Victoria. Both surface and subsoil may be sandier than in Hallam loam, and the transition may be shallower or deeper; but they all have in common the acid reaction, the grey surface and the heavier yellow subsoil. Soils with similar properties occur in the wetter regions of every continent, and the Russians have given them the name *podzol*. (This is formed from the word *zola*, for “ash”—both appearance and feel being ashy—and *pod*, underneath).

Podzolic soils throughout the world present similar problems to the farmer; they are chemically poor in nutrients and have poor natural drainage. Knowledge and experience gained in one part of the world may therefore be usefully applied to a similar soil elsewhere.

(2) The outstanding properties of Barmera sandy loam are: calcareous (i.e. free lime) throughout the profile, especially in the subsoil, where a layer of round masses of limestone occurs; alkaline pH's throughout, increasing with depth to values over 9; a brown or reddish-brown surface of light texture, the lower layers becoming gradually heavier; no ironstone. Besides these properties, the subsoil is often saline. These properties are common to many types in the Mallee, and the term *Mallee soil* has been given to them. All the members of Table 2 have these properties.

With these two illustrations, we can pass on to a general classification (see Table 6).

## SCHEME OF GENERAL CLASSIFICATION

Soils are first divided into two classes according to their content of organic matter. If this exceeds 20 per cent it dominates the physical properties, and the soil will burn. Such a soil is called a peat, or peaty, as opposed to the more usual soil in which the inorganic fraction dominates, and which is sometimes called a “mineral” soil.

The major subdivision of mineral soils depends on the presence or absence of free lime in the profile. This amounts to a separation into alkaline and acid,



since calcium carbonate is certain to be formed in an alkaline profile<sup>3</sup>. Each class is further subdivided here according to whether the subsoil is markedly heavier than the surface. This feature, like acidity and alkalinity, has an important influence on the growth of plants. There may be a further subdivision according to various other features of the profile which are described in each individual case. The final names, numbered 1 to 14 on the list, are among those known as the "Great Soil Groups" of the world.

TABLE 6  
THE SOIL GROUPS

I. MINERAL SOILS	
A. No $\text{CaCO}_3$ in profile	
(i) Contrast of texture in subsoil..	(1) <i>Podzolic</i>
(ii) No contrast of texture.....	(2) <i>Red loam or Krasnozem</i>
	(3) <i>Laterite</i>
	(4) <i>Braunerde</i>
	(5) <i>Meadow soils</i>
	(6) <i>Alluvial soils</i>
B. $\text{CaCO}_3$ in profile	
(i) Contrast of texture in subsoil..	(7) <i>Mallee</i>
	(8) <i>Red-brown earth</i>
(ii) No contrast of texture.....	(9) <i>Chernozem</i>
	(10) <i>Chernozem-like</i>
	(11) <i>Other soils with lime in profile</i>
II. PEATY SOILS .....	(12) <i>Lowmoor peat</i>
	(13) <i>Highmoor peat</i>
III. PARENT ROCK MAIN FEATURE OF PROFILE	(14) <i>Skeletal soils</i>
IV. MISCELLANEOUS	

The scheme of classification given here does not coincide with any that is given in the reference books (see p. 207), although the names of the groups have the meanings most usually given. The classification of soils is still in a confused state; it was only during the years 1925-30 that soil scientists agreed to classify on the basis of the profile, and there has not been enough time for international discussions to clear up the confusion, so that many books still give schemes that are based partly on profile, partly on geology, and partly on climate. Even when the present inconsistencies are cleared up, there will remain a large number of transitional soils which have to be placed in an

<sup>3</sup> Soils containing an accumulation of  $\text{CaCO}_3$  anywhere in the profile are called *pedocal*s in the technical literature (*pedon*, Greek for soil; *cal* stands for calcium). Those without  $\text{CaCO}_3$  are often called *pedalfers*, because aluminium and iron (*al*, *fer*) may be concentrated somewhere in the profile. *Pedocal* is a useful name, but *pedalfer* is not, and the word may lead to confusion, since some *pedocal*s have concentrations of iron compounds and so are apparently *pedalfers* as well, while some soils are neither *pedocal* nor *pedalfer*.



arbitrary way in one group, although they seem to belong equally to two groups; this problem, however, is not confined to soils.

#### FOURTEEN MAIN GROUPS

In this chapter most attention is given to local soils; for further description of other soils, overseas books may be consulted. In the examples quoted below, those profiles to which names are attached have been mapped in published surveys. Others have not been mapped, and therefore have not yet been named.

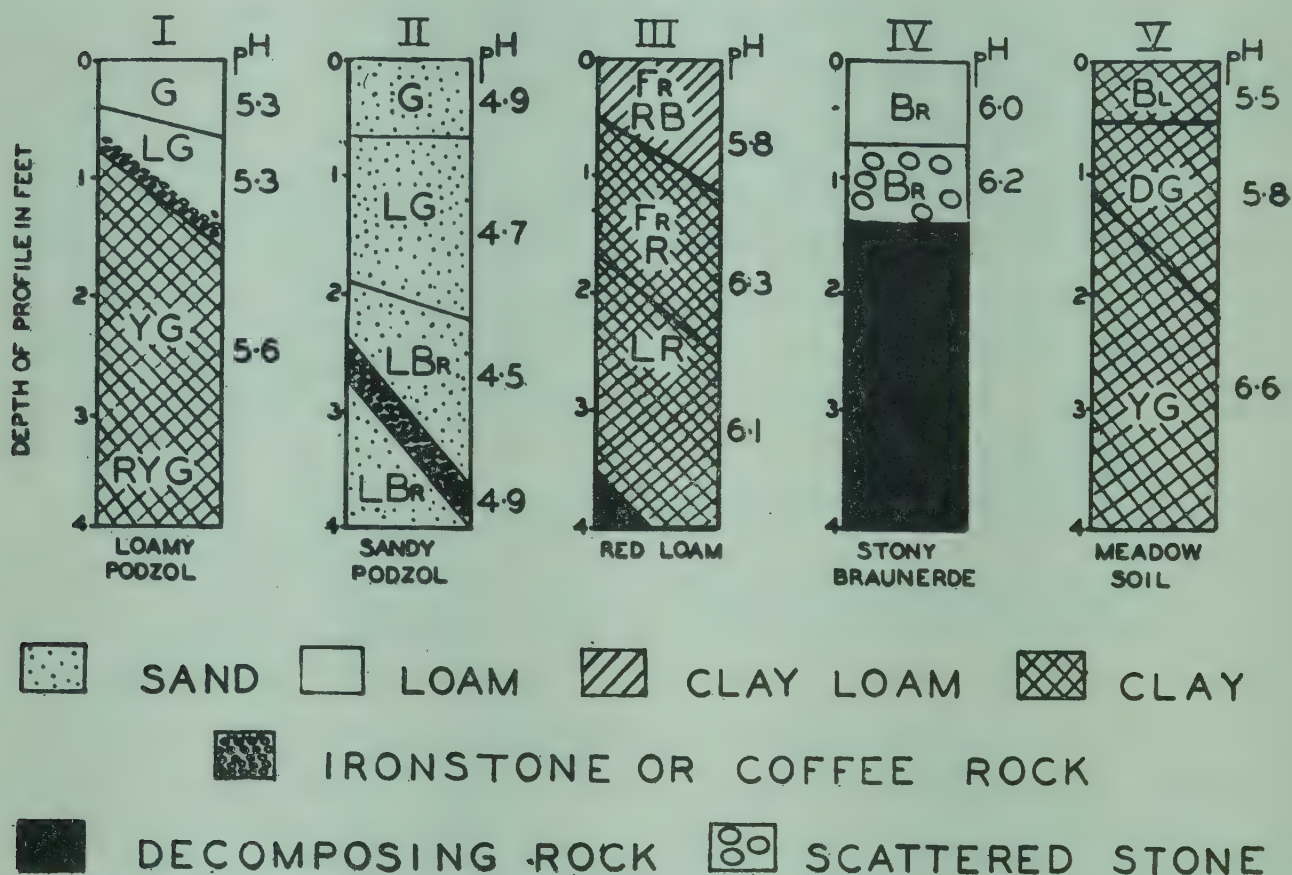


Fig. 4. Profiles representing five soil groups. The sloping lines indicate the limits within which the various transitions occur on the respective types—thus, the clay horizon in the loamy podzol I begins anywhere from 10 to 20 inches from the surface. The letters stand for colours: BR, brown; BL, black; G, grey; D, dark; L, light; R, red; Y, yellow; RYG, denotes a mottling of red with yellow-grey. FR denotes friable.

#### I (A). *Acid throughout Profile* (Fig. 4)

1. *Podzolic Soils*. The properties of these soils have already been described (p. 16). They may be thus tabulated:

(1) They are acid throughout the profile and contain no free lime.

(2) The colour of the surface is grey, often passing to very pale grey or white at a depth of four inches or so; the subsoil commonly has a yellow shade, sometimes with red mottling, or may be predominantly reddish. The whiteness of the subsurface is due to impalpable silica, known as “silica flour” (see p. 47). Some profiles show this in extreme form in the one inch immediately overlying the clay horizon.



(3) The surface soil has a fairly light texture while the subsoil is heavy; the transition from one to the other is sudden<sup>4</sup>. Even in the lightest types the subsoil, though not heavy by ordinary standards, is relatively so.

(4) Concretions of ironstone gravel from a millimeter to an inch in diameter are frequently, though not always, present at the transition from surface to subsoil. In sandy types these do not occur, but there is a layer of hard, dark brown material, known as "coffee-rock" at this level; this consists of sand cemented by organic matter and iron oxide.

Since podzolic soils occupy so much of the well-watered parts of Australia, two more profiles will be quoted here besides that of Hallam loam, already given. One of these represents a common type on basalt in the Western District of Victoria west of the Hopkins River, and the other the very poor sandy podzols which are especially common near the coast.

(a) Developed on Pliocene basalt, Moyne Falls, near Macarthur, Western District:

- 0- 8 inches—Grey loam to clay loam (pH 5.0).
- 8-14 inches—"Buckshot" very marked, maximum at 11 inches (pH 5.6).
- 14-18 inches—Yellow grey clay loam, buckshot diminishing (pH 5.7).
- 18-40 inches—Clay with yellow-red mottling, much heavier than above (pH 5.6).
- 40-60 inches—Similar, clay becoming heavier (pH 5.9).
- 60-77 inches—Similar, grey mottling apparent (pH 5.8).

This soil appears to have carried red gum originally; it is now used for grazing sheep. This profile is deeper than the average; rock is more common at a depth of three to four feet. The ironstone gravel, which is known in Victoria as "buckshot", often appears on the surface after erosion, and has been responsible for the name "Buckshot Plains" given to this part of the state.

(b) Developed on deep sandy river deposits, near Cranbourne, 27 miles south-east of Melbourne.

- 0-23 inches—Light grey sand (pH 4.7-4.9).
  - 23-46 inches—Light brown sand, becoming darker with depth (pH 4.3-4.6).
  - 46-60 inches—"Coffee-rock"—dark brown sandstone, cemented with organic matter, but fairly easily crushed (pH 4.9).
  - 60-64 inches—Reddish yellow clayey sand (pH 4.8).
- The underlying sand continues coarse.

This soil has been described and mapped as *Cranbourne sand*. It carries a mixed scrub and heath vegetation, with a few poor manna gums. In places it has been cleared and used for dairying. Some examples of this type are intensely acidic with a pH below 4 and after their heathy cover has been removed will

<sup>4</sup> The transition extends over as much as 6 inches in some podzolic types in the Victorian mountains, but the sudden transition is still a good general character of podzolic soils.



grow hardly anything but sorrel unless lime is applied. In other areas the sandy podzols with coffee-rock in the subsoil grow honeysuckle and grass-tree—e.g., the western coast of Wilson's Promontory (Plate IV).

Podzolic soils are chemically poor. This alone, however, does not condemn them, since it is worth while to make up deficiencies by means of fertilizers if the rainfall is adequate. But their poor physical condition is more serious. The surface soil has a poor "structure"—that is, it easily runs together to form a hard mass—except for the sandy types, which on the other hand may fall short of water during the late summer and autumn. The low permeability of the subsoil, however, is probably the worst fault of all but the sandiest types, since it may restrict roots to upper levels and also may lead to damage through waterlogging in a wet winter. This has been the trouble, for example, with many apple orchards on types like Hallam loam near Melbourne, and with attempts to grow wheat on land near the Hume Highway from Euroa to Benalla. In spite of the shortcomings of podzolic soils, first-class pasture has been established on many types in southern Victoria with no other treatment than adding superphosphate and sowing subterranean clover, which eventually builds up the fertility in nitrogen as well, enabling perennial rye-grass to succeed.

The deep sandy types like Cranbourne sand are so inferior to the others that American workers keep the word *podzol* for these alone, and call the others *Grey-brown podzolic soils*. The ideal podzol of the English and American textbooks is not only sandy but is overlain by several inches of acid litter, such as is easily formed by coniferous forest. Eucalypt forest, except in the gullies and on the highlands, forms no such deep carpet, but only a thin litter of twigs; however, the rest of the profile is similar enough to warrant using the same word, though certainly the word podzolic embraces a wide variety of soils. These soils in the wetter parts of Victoria are often naturally associated with one or more of the eucalypts known as peppermint, stringybark, and messmate.

2. *Red Loams, Red Earths*. In the first place, this group is an example of the unsatisfactory nature of the present system of naming soils. *Red loam* (or *red earth*) in technical discussion does not mean just any loam that happens to be red—as for example, some of the "red-brown earths" of the Werribee plains which are loams and are red. The term has a special, restricted meaning, as given below. This use of an everyday term with a technical meaning is unfortunate and must lead to a great deal of confusion. We could avoid the trouble by using a foreign word (like the Russian *krasnozem*, which means red land) or inventing a new word, as botanists and zoologists do. In this book Red Loam and Krasnozem are used interchangeably; here are the properties of the group.



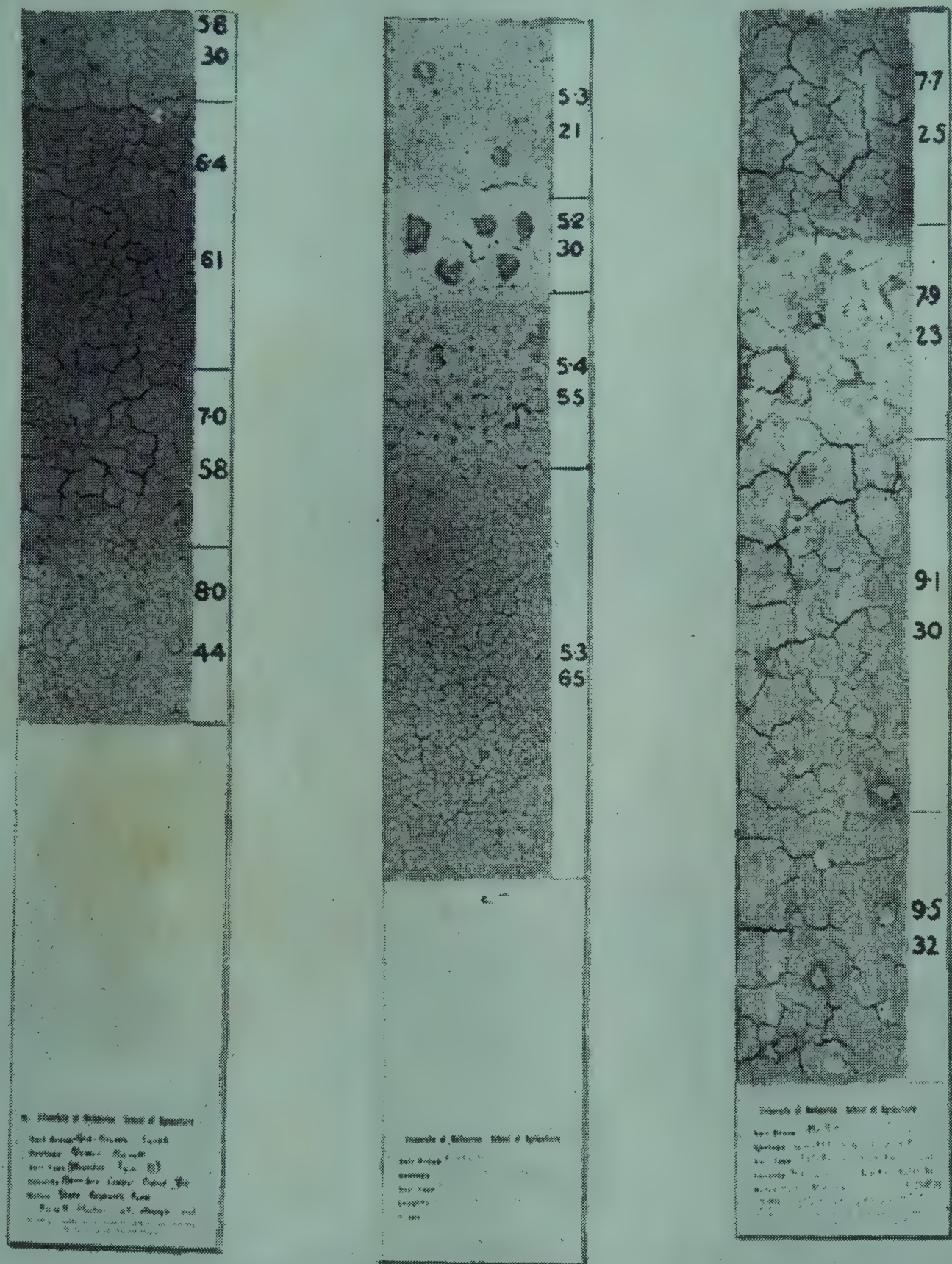


Plate III. Three-ply profile models, quarter-scale (18 inches long). From left to right—Red-brown earth, Podzol, and Mallee soil. The two figures for each horizon are pH and clay percentage, respectively. Note the lime in the lower horizons of the Red-brown earth and Mallee soils, and the pale sub-surface and iron gravel of the Podzol.





*Plate IV.* Sandy podzol on granitic colluvium, Wilson's Promontory, Victoria, showing the bleached sub-surface ( $A_2$ ) overlying the compact subsoil of clayey sand (B). Note the wavy boundary of  $A_2$  and B horizons.



- (1) They are acid throughout, with no free lime.
- (2) The colour of the uppermost six to ten inches is commonly reddish brown, but may be lighter or darker—anything from red to chocolate. Many look almost black when wet. The subsoil has a lighter colour, and is often bright red.
- (3) There is commonly no sudden change of any kind with depth, but the colour becomes gradually lighter (with less iron and organic matter) and the texture heavier. Some red loams can hardly be separated into horizons in the ordinary way, but an arbitrary separation is made, say at 9, 18, and 27 inches. In some types, however (e.g. at Mount Dandenong) there is a sharp change at about 12 inches to a heavier texture.
- (4) They are highly friable and permeable, even though many of them contain very little sand. This is their most important feature and is the origin of the term “loam” for the group. The connection of friable nature and redness is not accidental (see p. 78).
- (5) Many of them are “deep”<sup>5</sup>, and pass into decomposing rock well below six feet. However, “shallow” examples on basalt are common.

Two examples in Victoria follow:—

(a) At Kinglake, on the main Divide at a height of 1850 feet. The parent rock consists of clay deposited below the sea in the Silurian age and since consolidated to form “mudstone”. This type of rock covers hundreds of square miles to the east and north-east of Melbourne, usually giving rise to podzolic soil. At Kinglake, however, the soil type is different. In its natural state it carries heavy timber, including mountain grey gum. Some of the land has been cleared and used for growing potatoes. The profile is as follows:—

- 0-10 inches—Reddish brown clay loam, friable (pH 5.1).
- 10-20 inches—Light red, friable light clay (pH 5.4).
- 20-31 inches—Light red, light to medium clay, more plastic and sticky (pH 6.0).
- 31-56 inches—Red clay with yellow mottling (pH 5.5).
- 56-72 inches—Yellow tints predominating (pH 5.5).
- 72-100 inches—Yellow clay, like that commonly found over Silurian mudstone. Occasional stones begin at 100 inches, and pH rises sharply to 6.3.

(b) At Berwick, 30 miles east of Melbourne. This is representative of a type that is common in the south Gippsland hills, as at Mirboo North. The parent rock is basalt, which has weathered deeply and is marked “older basalt” on geological maps. This type originally carried dense forest, with tall eucalypts and blackwoods. It is now used mainly for dairying and carries “improved”

<sup>5</sup> Soils are often described as “deep” or “shallow”; these words refer to the depth to which the texture and colour of the surface persist. Thus soils with a claypan at six inches or rock at twenty inches are “shallow”. “Deep” soils allow roots to penetrate for several feet.



(i.e. introduced) pasture, in which subterranean clover, white clover, rye grass and cocksfoot are found on the best properties. The profile is as follows:—

0- 9 inches—Dark red-brown clay loam, rich in organic matter and very friable.

9-17 inches—Reddish-brown friable clay loam, with less organic matter than above.

17-27 inches—Red friable clay.

27-39 inches—Red friable clay mottled with yellow.

39 inches downwards—Light brown decomposing basalt, gritty loam in texture.

The pH is close to 6, being a little more acid in the surface horizon. Solid rock may not be found till several feet below the surface, but isolated stones of basalt, in a highly decomposed state, occur in some profiles fairly close to the surface. Ironstone concretions  $\frac{1}{4}$ – $\frac{1}{2}$  inch in diameter occur in the subsoil in small amounts. This type is mapped in Fig. 2 (p. 10).

Red loams, and red soils in general, have great prestige, which is not entirely deserved. The virtue of the red loams is that they are friable, deep and permeable. Potatoes in such soils grow a good shape and may be left a long time before digging. Further, the red loams occur in regions of good rainfall, and the combination of good rainfall and good drainage is a great asset, though during dry seasons the upper layers may become too dry for shallow-rooting plants. Chemically, however, they are not well supplied, and some types are very low in plant nutrients. Extensive areas of red loams occur in northern New South Wales at Lismore and Dorrigo, where summer rainfall is heavy. Both of these areas formerly carried heavy forest and are now closely settled, especially for dairying. However, yields have decreased seriously since about 1930, especially at Dorrigo, apparently on account of chemical poverty.

There is no foundation for the popular belief that all red loams are “volcanic”, though red loams on basalt are found from northern Tasmania to northern Queensland. There is certainly no evidence of volcanic action at Kinglake. Neither are they all high in iron; the removal of 4 per cent of free ferric oxide (p.198) removes the red from some Gippsland soils. The popular term “red mountain soil”, however, is sound; many of the red loams are found on divides (as at Kinglake, Trentham, Warragul and Berwick in Victoria) or in the mountains.

The *Terra rossa* of European writers appears to be similar to the above; the term is especially used for certain red soils developed on limestone in the Mediterranean region.

(3) *Laterites*. This term is the most unfortunate example of the present confusion in naming soils. Laterite originally meant a red clay occurring in the wet tropics from which the natives made sun-dried bricks (*later*, Latin for brick):



but nowadays it may mean anything from a "red loam" to a mass of ironstone, according to the author's choice—the reader has to discover the meaning from the context! In Australia, Prescott uses this word to mean concretionary ironstone occurring as gravel or as a solid mass on the surface; other writers in America use it for any soil, whether gravelly or sandy or loamy, which is red and rich in iron. This concretionary ironstone country is common in Western Australia, where it occupies much of the forested south-western corner, and is scattered in patches through the wheat-belt, greatly lowering the average natural fertility. It also occurs in large areas of Queensland, and in Kangaroo Island. The country where it occurs in Cape York Peninsula is called "wet desert". The ironstone weathers extremely slowly; in consequence, in hilly or sloping country the land may slope away abruptly immediately downhill from the "laterite".

The following profile represents this kind of soil in Victoria. It occurs along ridges at Anglesea, being derived from Tertiary sediments. The surface is covered with round ironstone pebbles up to an inch in diameter. The native vegetation resembles that of the surrounding acid sandy country, consisting of scrubby eucalypts (mostly messmate), heath, stunted honeysuckle, grasstree, and a cutting-grass (*Gahnia*).

- 0- 3 inches—Grey-brown clay loam, ironstone gravel on surface.
- 3-16 inches—Reddish-brown clay, friable, with ironstone gravel.
- 16-20 inches—Yellowish-brown heavy clay, with much red gravel.
- 20-45 inches—Yellowish-brown sandy clay, gravel decreasing and sandiness increasing with depth.
- 45 inches downwards—Bright red friable heavy clay mottled with white, apparently kaolin.

The features commonly met in such profiles, besides the gravel, are the yellow-brown clay and the mottling with kaolin. The pH of the above profile is between 5 and 6. The buckshot podzols of the far Western District have some resemblance to this profile.

(4) *Braunerde* or *Brown Forest Soil*. *Braunerde* is the German for brown earth. This is a common term in Europe, denoting a uniform profile with a good crumbly structure on the surface, good drainage, and a pH of about 6 throughout. It is associated in Europe with deciduous forest, for example the oak, and has 5-10 per cent of organic matter in the surface. Its natural fertility is moderately good. It has nothing to do with the "brown soils" of Prescott's map, which are alkaline. Perhaps the skeletal profile from Omeo (p. 32) is a *Braunerde*, but little is known of Australian members of this group.

(5) *Meadow Soils*. *Meadow soil* is a curious term, originating in an old use of the word *meadow* to mean periodically wet land, especially near a river. The



German *Wiesenboden* (with the same meaning) is also used. This is another bad name, since our classification is in terms of the profile itself and not of its situation or history. However, as with *red loam*, we must use the accepted words until the system is reformed.

These soils are acidic and become heavier with depth, but there is no sharp contrast between successive horizons except that the permeability to water becomes much less on passing below the arable layer. Mottled colours are very characteristic. An extreme development described in overseas books is *glei*, or a horizon with green, grey, and red patches visible, the green and red being due to iron in the reduced and oxidized state respectively.

An example is Eumemmering clay, which occurs in basins in the undulating land to the east of Melbourne. This land has been flooded from time to time during the last few centuries, and has thus received fresh material on its surface. It differs in this way from the surrounding podzols, which lie out of the reach of most floods, and from the red loams, which lie on hills or on the tops of divides. Eumemmering clay has the following profile:

- 0- 6 inches—Black clay, with some “self-mulching” tendency (see p. 29). Friable if worked at just the right degree of moistness. (pH 5.5).
- 6-16 inches—Dark grey clay, very plastic and very slowly permeable (pH 5.8).
- 16-33 inches—Light grey clay, impermeable (pH 6.6).
- 33 inches downwards—Light grey clay with yellow mottling. This clay extends for several feet (pH 6.7).

This type (Fig. 2) was described on a reclaimed swamp, which was formerly covered by swamp tea-tree, and was under water for several months in the year. Unlike the neighbouring peaty land of Kooweerup, which was formed under a permanent sheet of water, the surface layer of Eumemmering clay is heavy and difficult to manage, while the lower layers are so impermeable that they remain wet, even within three feet of a drain. The reclamation scheme in this case has simply provided a wide channel into which surface water can get away. Chemically this type is much better provided than the surrounding podzols; it is high in organic matter, though not high enough to be peaty; its main trouble is physical, namely its wetness in a wet season and its difficulty of working. For the most part it carries pasture.

(6) *Alluvial Soils*. This term is used to describe profiles that have developed on river alluvium and have no consistent relation between successive horizons. The heaviness may increase, decrease, or remain constant with depth, but there is no really heavy and compact horizon, as in the podzols or the red-brown earths. The profile, in fact, consists of successive flood deposits.



On the Macallister flats at Newry, in Gippsland, the following profile was found:

- 0-12 inches—Dark brown loam (pH 5.8).
- 12-33 inches—Light brown silty loam (pH 5.8).
- 33-42 inches—Lighter brown sandy silt (pH 7.2).

This is a naturally well-drained type. Both physically and chemically it is first-class. Soils of this nature grow heavy crops, and have been the basis for the belief that Gippsland is fertile. The fertility, however, in this part of Gippsland, is confined to river flats which have received deposits of fine material which the rivers have carried down from the mountain rocks.

Alluvial soils occupy only a minute proportion of the whole country. Yet some of them are very striking. Thus, Tarwin River in South Gippsland and Carlisle River in the Western District drain the poorest of sandy podzolic country, yet their alluvial flats carry first-class dairy pastures. This is due to two factors; firstly, the very slight chemical wealth of the hills is largely concentrated in the mud that is washed onto the flats, and secondly, water is available in the deep subsoil. Many similar contrasts of alternating podzolic country and alluvial soils occur in the far east of Gippsland and along the east coast of Australia.

Silty and fine sandy textures are common. However, an alluvial deposit can have any texture. The alluvial gravel of the upper Ovens river and the alluvial clay of some Murray river flats are much less attractive than the Newry type just quoted. All these profiles, however, share the property of being simply a succession of flood deposits and of having no regular relation of the horizons to one another. The red-brown earth developed on river deposits at Werribee is not an "alluvial soil", though it is often so called popularly. The term would lose all precision in meaning if it were extended to include any profile that was developed on material laid down by rivers.

Alluvial soils have here been included among the acid groups. This is generally correct for Australia, but an alkaline alluvial soil in limestone country is of course possible.

#### I (B). *Soils with $\text{CaCO}_3$ in Profile* (Fig. 5)

These groups, like those just dealt with, may be separated according to the degree of contrast between the surface and underlying horizons. Those in which there is a contrast may again be subdivided according to whether the surface is acid or is alkaline like the subsoil. We may start with the latter group.

##### B. (i) *Contrast in Texture in Subsoil*

7. *Mallee Soils.* These occur throughout the Mallee district of Victoria, as well as in the adjoining Murray Mallee of South Australia and elsewhere in South



Australia and Western Australia, mostly where the climate is similar to the Victorian Mallee. The name is taken from the eucalypts, fairly small species of characteristic habit, which dominate the native vegetation in those parts of Victoria and South Australia. The name again can be criticized since Mallee soils and mallee vegetation are not always associated even in Victoria—in Western Australia they are not associated at all. But the alternative, “Brown calcareous solonized soils”, is not attractive either.

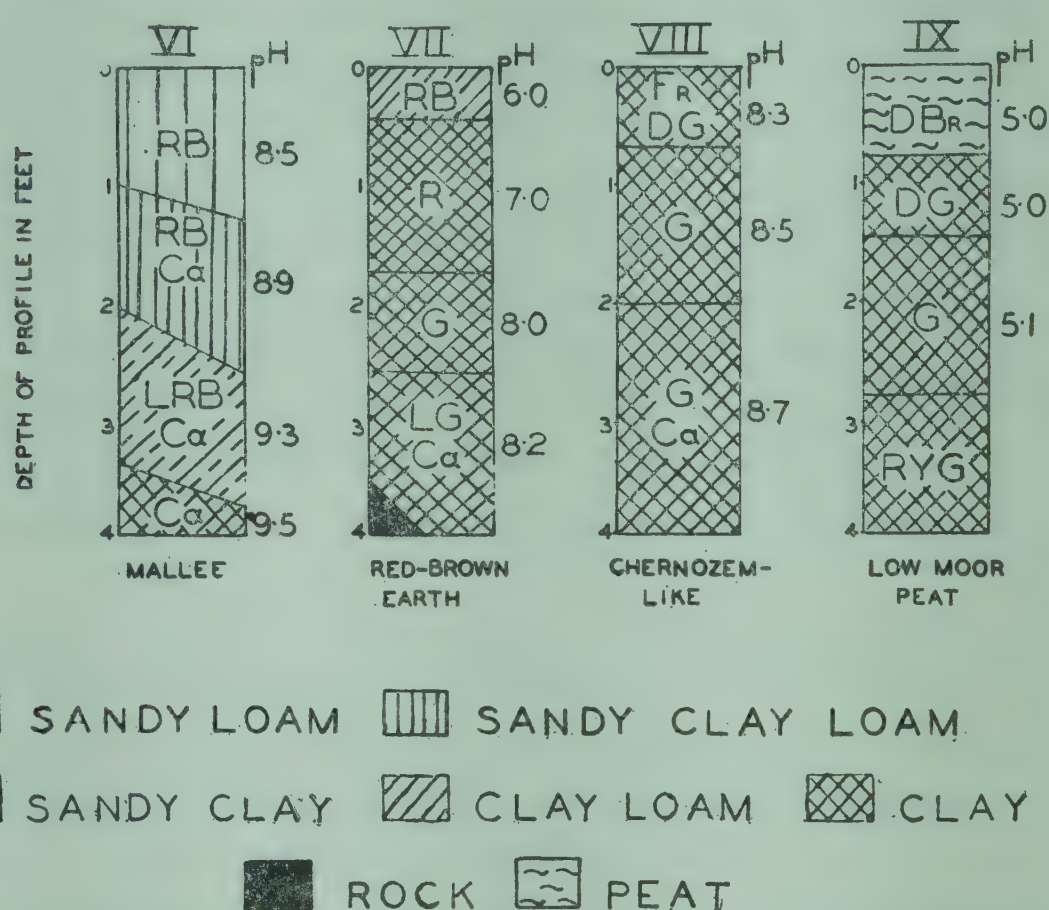


Fig. 5. Profiles representing four soil groups. The Mallee soil is Tatchera sandy loam, common in the Swan Hill district. The other three correspond to those described in the letterpress. The abbreviations are the same as in Fig. 4; Ca denotes calcareous.

Mallee soils have the following properties (compare Plate V):—

- (1) The profile is alkaline throughout, with much free lime in the subsoil.
- (2) The surface is brown, greyish-brown, or reddish-brown, the subsoil is light reddish-brown.
- (3) The subsoil is heavier than the surface.
- (4) A layer of limestone pebbles at about two feet is common, being a little deeper in the lighter profiles. These pebbles are often spoken of as “rubble”.

Barmera sandy loam, already described, is a good representative of the group, and the whole association from sandy rise to relatively heavy flat belongs to the group. Murray sand (p. 7) shows only a slight increase in heaviness in the subsoil, but is similar to the neighbouring Mallee types in other ways, so that it must be put in the same group. Mere wind-blown loose sand,



however, does not make a Mallee profile; parts of the Victorian Mallee can only be described as sandhills, and do not fit into any group.

The Mallee soils are fairly saline, though rarely saline enough to affect the growth of wheat, for which they are predominantly used. Salt has, however, caused trouble with irrigated crops, especially oranges (p. 171).

The term is, of course, not used in other countries; the "brown soils" of America might be related.

8. *Red-brown Earths*. This technical term has not been used outside Australia. As with "red loams", the meaning is restricted to a group of soils with more in common than merely the colour of the surface. Their properties are as follows:—

- (1) The surface is usually on the acid side, though it may be neutral. The subsoil is neutral to alkaline, becoming more alkaline with depth. Commonly the upper subsoil (above 30 inches) is free of lime and the lower subsoil contains lime as streaks or concretions.
- (2) The colour of the surface is reddish-brown, the upper subsoil is red. The lower subsoil may be light brown or grey.
- (3) There is a sharp transition from a relatively light surface to a heavy subsoil commonly at a depth of about six inches.

The two following profiles represent the main occurrences in Victoria<sup>6</sup>:—

(a) Developed on basalt, Werribee plains:

0- 5 inches—Reddish-brown clay loam, often sticky in wet weather.  
pH from 6.0 to 6.5.

5-20 inches—Red clay, only slowly permeable. pH about 7.

20-30 inches—Grey clay, of pH about 8.

30-40 inches—Calcareous clay, white and crumbly.

The calcareous horizon lies above the rock. Lumps of solid basalt (called *floaters*) ranging from an inch to a foot in diameter occur throughout the profile. Rocks lay over most of the surface originally, but have been removed from the ploughed layer. These were built into stone fences which were once a general feature of the country but have now mostly been removed and crushed to form roads.

(b) Developed on river sediments, Katamatite, North-Eastern District (Moirra loam):

0- 6 inches—Brown loam, cloddy when dry (pH 6.4).

6- 8 inches—Light brown loam, slightly cemented; a bleached version of the surface soil, sometimes mixed with above layer by cultivation.

8-27 inches—Brown to red-brown heavy clay (pH rising from 7 to 8.5 at lowest level).

27-40 inches—Mottled yellow-brown heavy clay with lime both as streaks and as concretions (pH 9.2).

40-72 inches—Mottled yellow-grey clay becoming lighter with depth, with a little lime, (pH 8.5-9.0).

<sup>6</sup> A typical occurrence in South Australia is at the Waite Institute at Adelaide.



Similar soils to this are common in the irrigated Goulburn Valley as well as in the North-Eastern District of Victoria. The compact clay just below the surface is their worst feature, as it may hinder the penetration of water or of roots. This may be a bright red, especially in the Goulburn Valley. The surface soil is often silty and hard when dry. Similar soils also occur in the Wimmera, where they form a complex with the more desirable grey soil (p. 13).

The red-brown earths may be described as of fair average quality. They make up a substantial proportion of the wheat-belt of south-eastern Australia.

The *degraded chernozem* of Russia appears to be similar in many ways to the red-brown earth, but the red tint of the surface horizon is lacking.

#### B. (ii). *No contrast of Texture in Profile*

9. *Chernozems*. Of the groups with no contrast between surface and lower layers, the most interesting is the *chernozem*<sup>7</sup>. This word is the Russian for black land. This group covers a huge area both in Russia and in North America. The surface is black, has a pH of 7 to 8, contains about 8-10 per cent of organic matter, and has an excellent granular structure, making it physically an ideal soil. The common statement is that a spadeful tossed into the air falls apart like a bunch of grapes. Chemically it is also rich. The character of the surface soil persists to about two feet deep, with organic matter gradually decreasing, and streaks and concretions of lime are common between the second and third foot. Eventually the decomposing parent material is reached without passing through any relatively heavy horizon.

The chernozem is associated in nature with perennial grasses both in Russia and in America. Much of it is used for wheat, though in some places the climate is too dry for this.

*Rendzina* is a Polish word for a profile similar to that of the chernozem; the word is kept for soils formed on limestone, though this use is a departure from the principle of classifying according to the profile alone. It might perhaps be used to describe a shallow, skeletal chernozem. Some slopes of the Barrabool hills near Geelong are of this nature, but the flatter tops of the hills are mainly podzolic.

True chernozems are rare in Australia.

10. *Chernozem-like Soils*. This term is used for soils that resemble the chernozem in being alkaline, dark, and good in physical structure, but contain less organic matter, are dark grey rather than black, and have not the perfect crumb structure of the chernozem. Probably the best place to draw the line between these two groups is at 5 per cent organic matter; all soils below this figure can only be

<sup>7</sup>The reason for the curious spellings sometimes seen (tschernosem, podsol) is that the Russian work was first translated into German, and these are the German spellings.



“chernozem-like”. The biggest extent of such soils in Australia is in the sub-tropical parts of Queensland and New South Wales on the dry side of the Divide, including the Darling Downs. Another substantial occurrence is in the Wimmera. In all these places the surface is grey when dry, but looks black when wet, so that these soils are locally called black. The following is a profile of such a “black” soil from Natimuk, in the Wimmera.

0- 8 inches—Dark grey friable clay, self-mulching, a few pockets of lime.

8-24 inches—Similar, colour gradually lightening.

24-36 inches—Grey light clay with lime increasing to maximum.

Calcareous clay continues to below 6 feet. The pH rises from 8.3 in the surface to 8.5-8.7 in the subsoil.

The term “self-mulching” applied to a soil implies that when it dries after rain it breaks spontaneously into fragments less than half an inch in diameter. These fragments lie loosely over the surface like well-cultivated soil that has been worked to a fine state, so as to form a cover or “mulch” over the surface. This property is connected with the presence of free lime in the surface. The soil thus forms a good seed-bed which is one of its virtues for wheat-growing. The soil is so easy to work nowadays that farmers are surprised to hear them called clay, which in fact they are, as is evident in wet weather, when the mud of the Wimmera is impassable.

The subsoil swells greatly on being wetted, and this may crack the walls of houses founded on it; during the dry season great cracks develop to a depth of as much as three feet.

Another peculiar feature of these soils is that the natural surface is hummocky; such land in Victoria is called “crab-hole”. Only soils of uniformly clayey texture have this feature, which occurs in an extreme form in the Wimmera (see p. 52).

Other chernozem-like soils occur on the basalt of the Central and the nearer Western District. The small black patches among the red at Werribee have already been mentioned. Presumably, the parent rock here contained calcium carbonate. A more widespread black and friable type occurs round “stony rises” of basalt outcrop; this has a characteristic natural vegetation of shore thistles. Presumably the drainage water from the stony rises raises the calcium level of these thistle zones. Wherever such good black soil occurs, it is locally called “real volcanic soil”! This can be associated with other black and calcareous soils in basaltic country near Melbourne, often seen on the banks of creeks. The soil changes suddenly on the banks of creeks such as the Kororoit and Jackson’s creek, from a difficult grey clay to a dark and crumbly type. Apparently this is due to sideways and downwards movement of water that has passed through the calcareous subsoil of the plains. The soil of Merri creek,



famous for cricket pitches, is similar, though here the friable black soil extends beyond the creek's banks.

11. *Other Soils with Lime in Profile.* The remarkably vague terms, *grey soils*, *brown soils*, and *chestnut soils*, are used in the text-books on soils to describe profiles which are low in organic matter, alkaline, with free lime in the subsoil or throughout the profile, and with no marked contrast in texture; some of these may be high in NaCl. A zone of gypsum crystals may also occur below the lime (gypsum is the only material which appears in soil profiles in large crystals). Their most important difference from the previous group is that the heavier members have a poor surface structure. The following examples are taken from Victoria.

(1) Heavy grey soil on basalt in the nearer Western District. The following profile is mapped as Grenville clay (Diagonal shading, Plate II):

- 0- 7 inches—Grey clay, dries to hard clods (pH 6.0).
- 7-36 inches—Grey clay, very heavy (pH 7.0).
- 36-42 inches—Yellowish-grey calcareous clay. The yellow tint appears just above the free lime (pH 8.0).

Fresh basalt is common at a depth of about three feet. As with the red-brown earths of Werribee, "floaters" of basalt occur through the profile, and boulders lie over the surface in some parts. Small concretions of ironstone gravel (1-3 mm.) are scattered through the profile in small amounts. Much of this country is held in large sheep stations and still carries native pasture dominated by wallaby and tussock grasses, though some has been improved and carries subterranean clover and Wimmera rye-grass. Similar soils occur in the western suburbs of Melbourne, and are difficult for gardeners to manage. The subsoil is often saline, but any trouble arising from this is confined to small patches (cf. p. 173).

(2) A group of soils from northern Victoria may also be included here—the so-called "grey plains" and "red plains". The former have a better local reputation, but they are similar enough in texture and other characters to be dealt with together. At the same time, the "red plains" (which are often more truly brown) have some resemblance to the "red-brown earths", differing mainly in their uniform heaviness. Kerang clay, of the "grey plains" of the irrigated pastoral country between Kerang and Cohuna, has the following profile:—

- 0- 2 inches—Grey clay loam (pH 6.5-7.0).
- 2-28 inches—Grey to yellowish grey heavy clay (pH rising to 8).
- 28-84 inches—Yellowish grey clay with a little lime and small pockets of gypsum.

The deeper horizons are sometimes fairly permeable, in spite of their heavy feel, on account of having a well-marked structure (cf. p. 101).



This is also natural grassland, and much of it still carries wallaby grass or *Stipa*. The subsoil is highly saline, and this salt has reached the surface under irrigation with disastrous results.

Similar heavy soils occur in the Riverina; Niemur clay, in the Wakool Irrigation district, has been used for growing rice on account of its great ability to hold water.

## II. Peaty Soils

These have been defined as containing over 20 per cent organic matter, which is enough to dominate the physical properties; such soils can burn. In fact, fires in peaty land can be serious; they smoulder indefinitely and can only be put out by digging a trench across their path. Evidence of past fires is often seen in the brick-like ash that occurs just below the surface. Peat in the strictest sense of the word contains at least half its weight as organic matter, but peaty types with 20 to 50 per cent organic matter share some of the properties of true peat, so are dealt with here.

All these soils occur in naturally wet situations. Before they can be used they must first be drained, and in the process they shrink enormously. The main distinction among peaty soils depends on the nature of the organic matter and the extent of admixture with inorganic matter. We will take two groups:—

(1) Highly acid, predominantly organic, chemically very poor, resistant to microbial decomposition after draining.

(2) Acid or neutral, inorganic component high, chemically moderate, susceptible to microbial decomposition after draining.

12. *High-moor Peat*. The first group is called “high-moor” peat. It occurs in flat and wet, but not submerged areas in cool and wet climates and commonly consists of residues of moss species. This is so in Western and Southern Tasmania, where much the largest extent of high-moor peat in Australia occurs; somewhat similar soils in the same region are built up by button-grass. The streams running off this land are deep brown; the Gordon River of Western Tasmania shares this colour with many streams of Scotland and Ireland.

Highmoor peats may be several feet thick. The mainland peats of the High Plains of Victoria are mostly thin. These peats are of little value anywhere in the world. They are used in some countries for fuel, and in others for litter.

13. *Low-moor Peat*. The “low-moor” peats are very different, and many of them have a reputation for growing big crops. While these vary among themselves, Kooweerup peaty clay, which covers 23,000 acres near Kooweerup in Victoria, may be taken as representative.



- 0- 9 inches—Brownish grey peaty clay (pH 4.9).
- 9-17 inches—Dark grey gritty clay (the grittiness is due to angular fragments of quartz and feldspar).
- 17-33 inches—Grey gritty clay, some yellow and red mottling. This character persists to much greater depths, with a lighter grey below 33 inches. The pH is close to 5.0.

The surface soil contains more clay than peat, and yet does not feel clayey, but is loose and powdery when dry, and has a distinctive friable feel when moist. Such soils in U.S.A. are called "mucks". All the peaty types of Victoria are acidic, like that quoted; however, alkaline peats exist, for example the fertile "fens" of England, and small patches near Albany, W.A. In many of these, fairly firm clay occurs in the second foot. This is an advantage, since the underlying clay can be worked into the surface soil and so make it more compact, which is sometimes desirable.

The name low-moor is due to the formation of these soils in lakes; reeds and sedges grow in the shallow water and their residues are mixed with deposits of mud. The residues of these plants are far richer than those of the high-moor plants, both in nitrogen and in other nutrients.

Low-moor peats are physically excellent, and are intensively cultivated. One third of the former swamp of Kooweerup was cropped with potatoes in 1923. The two advantages of the peaty soil for potatoes are the open surface soil and the excellent drainage of the subsoil, which is honeycombed with wide cracks and cavities. Chemically, however, it is only mediocre.

All kinds of layering may occur in districts of peat formation. Peaty clay over clay is characteristic, sometimes with a deeper peaty surface than that quoted, but a reversal of this order occurs in Dalmore clay, which adjoins Kooweerup. The surface soil of this type is a black friable clay, with over 10 per cent of organic matter; clay continues to 30 inches, at which level is a horizon of 4 inches of pure peat, with more clay below. This type is one of the most fertile in the state, and grows big crops of vegetables and potatoes.

### III. *Skeletal Soils*

14. A soil is called *skeletal* if the parent rock occurs at or close to the surface. The characteristic skeletal soils are found in the mountains, where one would expect to find soils that are shallow on account of erosion. Thus, on the foothills of Mount Mesley, near Omeo, the following profile occurs on a slope of 30 degrees, under white-gum forest:—

- 0- 8 inches—Brown sandy loam.
- 8-14 inches—Lighter brown loam, stony.
- 14-24 inches—Weathered micaceous schist, some of which is soft; loose, friable material lies between the stones.

The pH is close to 6.



This country has been used for grazing; good grass still grows under the forest in some places, but where the land has been overstocked there is little ground cover (Plate XII). On some steep slopes the surface itself is stony; red stringybark grows on many of these areas.

Another skeletal type (Corangamite stony loam) occurs on the "stony rises" of the basalt plain of the Western District of Victoria (see Plate II). These rises may be only ten to thirty feet above the general level of the plain, but they are steep and the soil is thin. The soil is a friable brown or chocolate loam, from three to twelve inches deep, of pH about 5.5; in places it is little more than a filling between two rocks. It carries a better kind of herbage than the surrounding type of Grenville clay. In some parts, notably south and west of Lake Corangamite, the whole country consists of stony rises.

The only generalization one can make about skeletal soils is that they are too steep or too stony for agriculture. Their value for grazing or forestry is determined by the parent rock, which may be rich or poor in nutrients and may or may not allow roots to penetrate down vertical cracks. The thin soil formed on the sandstone of the Grampians is an example of a poor skeletal type, of which there are many.

The term "parent rock" in the definition of skeletal soils could be taken to include fine material, such as fresh river alluvium and volcanic tuff. Soils containing these materials, however, are so much more valuable and have such different profiles from stony skeletal soils that such a literal definition would not be useful. "Skeletal", in fact, is merely an ugly word for "stony". The American term is Lithosol.

#### IV. *Other Kinds of Soils*

(a) *Marked in Map* (Fig. 7). 1. The Jurassic hills of the Otways and Strzeleckis (marked "A"). The soils on these hills are podzolic, with a grey surface and a heavy yellow subsoil, yet they are distinctive enough to be worth marking separately. They have skeletal properties, with decomposing rock often close to the surface. This rock is simultaneously fresh enough and highly enough decomposed to contribute to the chemical wealth, so that the soils are above the average for podzols.

The country is steep, but much of it has been successfully used for dairying.

2. The flat land north and west from Sale (marked "B") is intermediate between podzol and pedocal, with an acid surface and an alkaline subsoil containing small lime concretions. Similar transitional soils occur in the podzol belt north of Euroa, near the margin of the red-brown earths.

3. Small isolated areas of soil in the Western District of Victoria lie over volcanic tuff. This finely divided material fell as ash or mud within a radius of a



few miles of several volcanoes, the most important of which are marked, namely Tower Hill (Koroit), Mt. Leura (Camperdown), Buninyong (near Ballarat), Mt. Noorat (Terang), and the Warrions (Colac). This tuff weathers into very rich soil; some has been used for growing onions—which are usually confined to first-class soil. If we allow the term “volcanic soil” to be used at all, we should confine it to these areas—but it is better not to use the term (see p. 60). The following profile was observed at Coragulac, near Colac.

- 0-5 inches—Chocolate clay loam, with a few stones (pH 6.0).
- 5-15 inches—Similar, with scoriaceous basalt (pH 6.5).
- 15-21 inches—Brown medium clay with stone (pH 7.1).
- 21 inches downwards—Volcanic ash.

A similar rich soil is formed on the volcanic material from Mount Gambier, South Australia. This is a chocolate sandy loam; in patches this contains free calcium carbonate.

4. Three unsettled areas occur in north-western Victoria. Poor mallee vegetation is common, but the prevalent soil is not a Mallee soil, but a featureless white sand. This is mapped “Sand without profile”.

(b) *Unmapped*. The soil map of any large area, whether Australia or Victoria, is only possible if we restrict ourselves to the dominant kinds of soil in each district. Types which occupy only small areas have to be ignored, though their peculiar properties may make them locally important. Some of these belong to groups which are better known in other parts of the world. Others are impossible to fit into any scheme. One example is given here.

Black soils occur on deeply weathered basalt, in the regions occupied by red loams in the east Central District and nearer Gippsland. These soils alternate with the redder types; in fact, every gradation from red to black can be seen. The black types are friable and loamy at the surface, but are less friable than the red loams in the lower horizons, and hold water better against drought. They are also higher in calcium than the red types, and have a pH value about half a unit higher in the subsoil. The difference in colour at the surface is not due to different amounts of iron or organic matter. The black types seem to have developed organic matter of a deeper shade under the influence of a greater concentration of calcium. There is an interesting parallel in the basalt country around Lismore, N.S.W., where the flat and undulating basalt plateau is red, and the slopes from the plateau to the plain are black and richer in calcium and magnesium.

Other groups not mentioned here include those associated with excess sodium—solonchak and solonetz. These are described on p. 161.



## COMMENTS ON MAPS (Figs. 6, 7)

Detail is sacrificed to an increasing degree as the scale of the map is changed. In the map of the County of Mornington (Fig. 6) the soil type has disappeared, and the association of Fig. 2, comprising the podzolic slopes and the black flats, becomes the new mapping unit. In turn, all the various associations in which sandy podzols and loamy podzols dominate are marked in the State map (Fig. 7) as "podzolic".

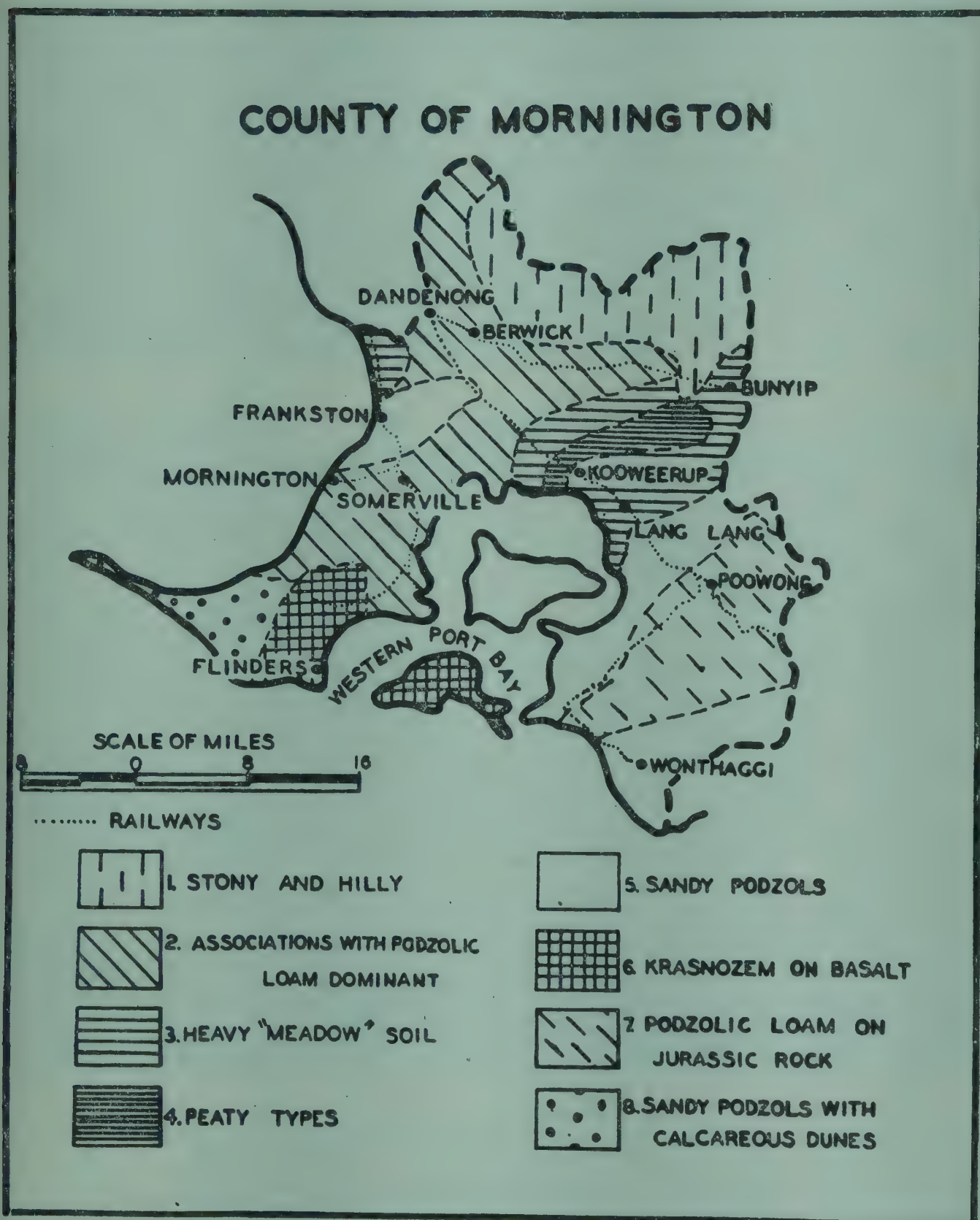


Fig. 6. Map of Soils of County of Mornington.



# SOIL MAP OF VICTORIA

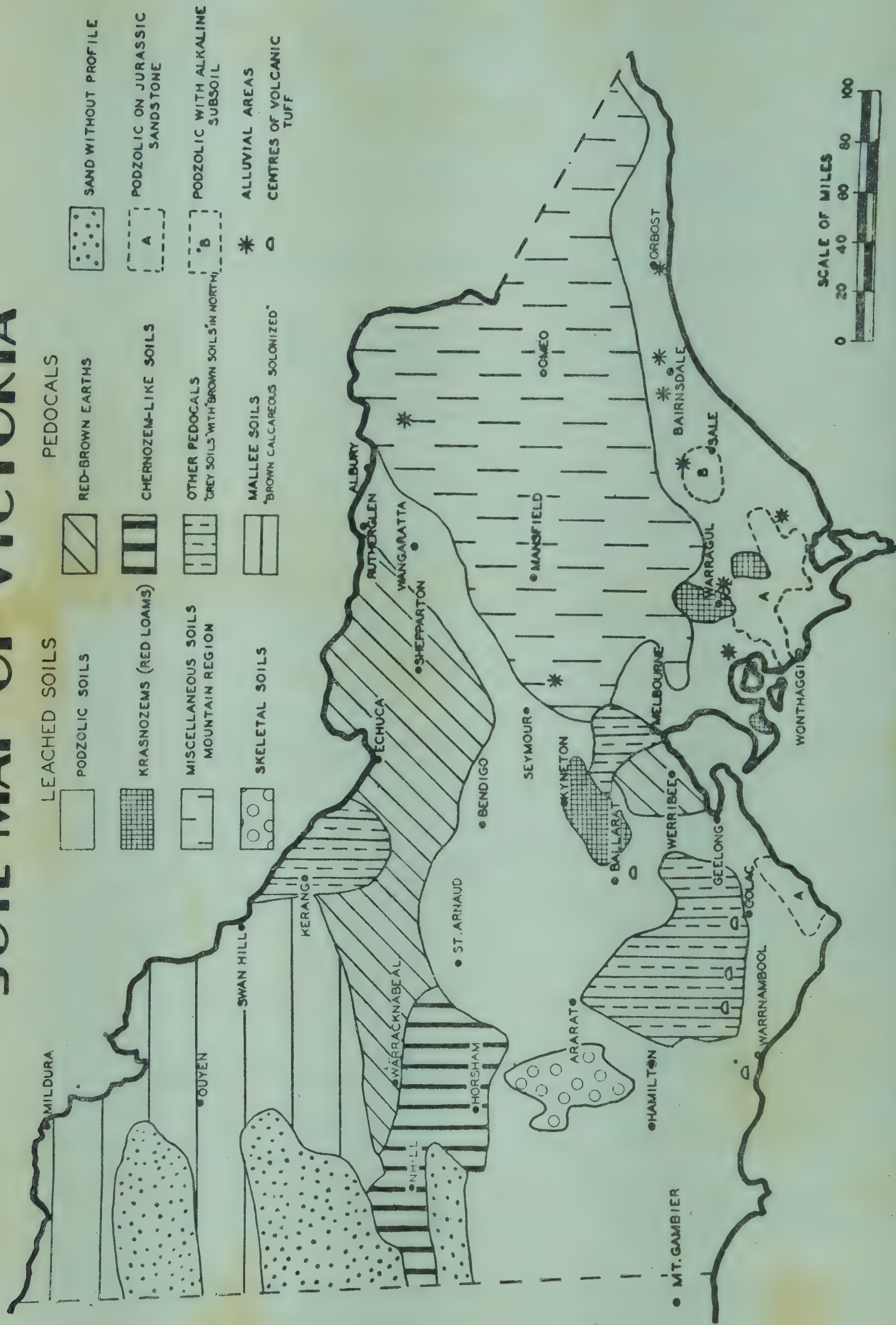


Fig. 7. Map of Soils of Victoria.





*Plate V.* Two pedocals. Above, Mallee soil near Hopetoun, Victoria. Red-brown sandy loam overlies lighter-coloured calcareous sandy clay loam with limestone nodules at about 15 inches (Photo, J. S. Turner). Below, Renmark loam, Renmark, South Australia. Surface (S) is at second rung of ladder. Lime layer lies below this (L), and gypsum layer begins just below fifth rung (G). Excavated material lies on the surface (Photo, T. J. Marshall).





*Plate VI.* Chernozem-like soil near Hobart, Tasmania. Note granular structure of surface, coarsening with depth, with lime below (Photo, C. G. Stephens),



The mountainous country of eastern Victoria has not been mapped in detail. This is partly because of its complexity; the narrow river valleys, which can hardly be shown on this scale, comprise most of the settled areas. But in any case a map of the soil of the hills and mountains themselves could not be made today, for lack of information. Stony and gravelly soils, red loams, podzolic types, and others occur on the slopes; a small area of high-moor peat, much of it shallow, occurs on the Dargo and Bogong "High Plains" at a level where the snow lies in winter.

Other areas might be improved by further subdivision than is attempted here. In the Mallee the main distinction is probably between the highly calcareous, even stony, types of the north, and the less calcareous types of the south. The former soils, which are poorer agriculturally, occur frequently to as far south as the Murrayville-Ouyen line. Again in the podzolic areas of the Western District, the parts where sandy types are more prevalent might be marked separate from the rest.

In parts of the state where different groups of soils intermingle, it is often a matter of individual choice where to put the boundaries. This applies notably to the tongue of red-brown earths extending south of the Mallee. Other notable examples of mixtures are in the krasnozem area to the east of Ballarat (where podzolic soils are common) and in the podzolic corridor running north from Geelong (where red-brown earths also occur).

The areas of alluvial soil are too small to delineate on this map. Since they are important out of all relation to their size, the main occurrences are marked with an asterisk; the Mitta and the upper Goulburn valley at Yea in the "mountainous" region, and Darnum, Yarram, Maffra, Lindenow, Bruthen, and Orbost in the podzolic region of Gippsland. Kooweerup, where the greatest area of lowmoor peat occurs, is similarly marked.



## CHAPTER III

### SOIL FORMATION

#### ZONAL DISTRIBUTION OF SOILS

THE MAP OF VICTORIA SHOWS HOW EACH GROUP OF SOILS IS DISTRIBUTED IN a zone. Naturally such a map involves great generalizations. The podzol zone includes many soil types which, though acid, are not podzolic (see pp. 21, 24), but which do not occupy a large proportion of the zone, and are not included on this small-scale map except for a few more important areas, such as the colluvium or hill-wash at the base of the South Gippsland hills, a few river flats, and the country surrounding a few volcanoes in the Western District.

Allowing for these generalizations, podzolic and other acid soils occupy the south, where the climate is cooler and wetter; alkaline soils are confined to the hot and dry north; the intermediate kinds of soil are in the intermediate climates, including the dry belt of the Central and Western Districts (compare Fig. 11) and the better-watered areas of the north.

This relation between soils and climate has been found in every continent. Acidic and chemically poor soils occur in the wetter climates, and neutral and alkaline soils—usually richer—in the drier climates. This relation was first discovered in Russia (Fig. 8); that is why Russian terms, such as podzol and chernozem, are now commonly used. Similar zoning is well shown in North America<sup>1</sup> and in the continent of Australia<sup>2</sup>, where the zones succeed one another in rings from the coast inland (see simplified soil map of Australia, Fig. 9).

*Leaching.* The wetter the climate, the more rain-water runs through the soil. Since the water always dissolves something in its passage, even if only in minute amounts, soluble material is constantly washed down into the deep subsoil. Whether the water then reaches a river, or is added to underground storage, the effect on the soil is the same—some of its reserves of elements have been lost. This process is called *leaching*. The metals sodium, calcium, magnesium, and potassium are lost (often in that order), with bicarbonate as the most important anion, together with sulphate, silicate, and sometimes chloride and nitrate. By the loss of metallic bicarbonates the soil becomes progressively more acidic. Besides these metals, iron and aluminium are also leached from the surface horizons of podzolic soils and deposited in the subsoil.

<sup>1</sup> See *Soils and Men*, pp. 365 and 865; and Kellogg's pamphlet, U.S. Dept. Ag. Miscellaneous Publication No. 229.

<sup>2</sup> Prescott, *The Soils of Australia*, C.S.I.R. *Bulletins* 52, 177.





SOILS OF PART OF U.S.S.R.

- |                          |                        |
|--------------------------|------------------------|
| PODZOL                   | OTHER PEDOCALS         |
| DEGRADED CHERNOZEM       | SALT-AFFECTED PEDOCALS |
| OTHER CHERNOZEM          | WINDBLOWN SAND         |
| "FAT" CHERNOZEM          | BRAUNERDE              |
| MEADOW SOILS OF CAUCASUS |                        |
| MISCELLANEOUS SOILS      |                        |

Fig. 8. Soils of part of U.S.S.R. (Prassolov, 1927). Omitting the Caucasus region, the climate becomes hotter and drier from north-west to south-east. The July isotherm for 20°C. runs roughly from Kiev through Moscow to Kazan; for 23°, through Odessa, Rostov, and north of Stalingrad. The 21-inch rainfall line runs from Kiev to Moscow and north of Kazan; the 16-inch from Rostov to Kuibishev. Stalingrad has 11 inches, Astrakhan 8. The "fat" chernozem is the richest in organic matter. The Azov chernozem (unmarked), formed on basalt, runs south from Rostov. The "other pedocals" comprise so-called chestnut, brown and grey. The soils south of the Caucasus are too complex to be mapped on this scale.



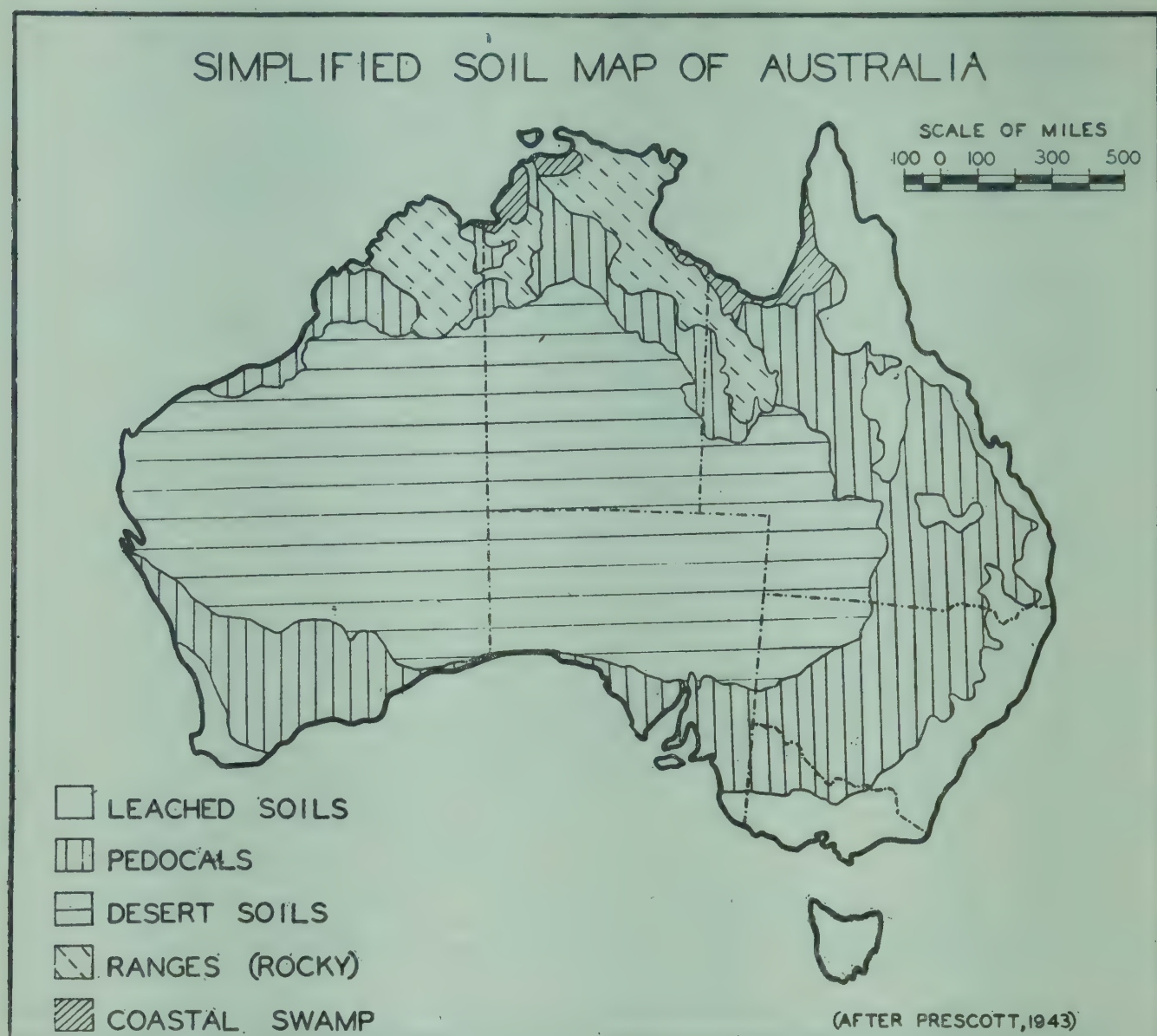


Fig. 9. Simplified Soil Map of Australia.

In the drier parts, including the country to the north of the ranges in Victoria, the rains of the winter seldom penetrate deeply. Thus, bicarbonates may be washed down one to three feet, but no further; the pressure of carbon dioxide is not enough to hold them in solution, and calcium carbonate with a little magnesium carbonate is deposited in a somewhat analogous manner to a stalactite in a limestone cave. In this way a zone of nodules of calcium carbonate is formed at the depth of penetration of the winter rain. Almost all soils in the drier climates contain enough calcium in the first place to make this possible, even if only on a small scale. This downward movement is not great enough to leave the surface acid. In many places where sodium chloride has accumulated in the profile it would even be better if leaching were more marked. Calcium sulphate also accumulates in dry climates, at a lower level than the carbonate, as the crystalline gypsum.

The downward movement of salts is one phase of leaching; but a further action may follow—namely, a downward movement of the finest clay<sup>3</sup> in

<sup>3</sup> The term "clay" is used in this chapter to mean *very fine material*, as defined in chapter VIII, and not a *heavy horizon*, as in the preceding chapters. See too p. 110.



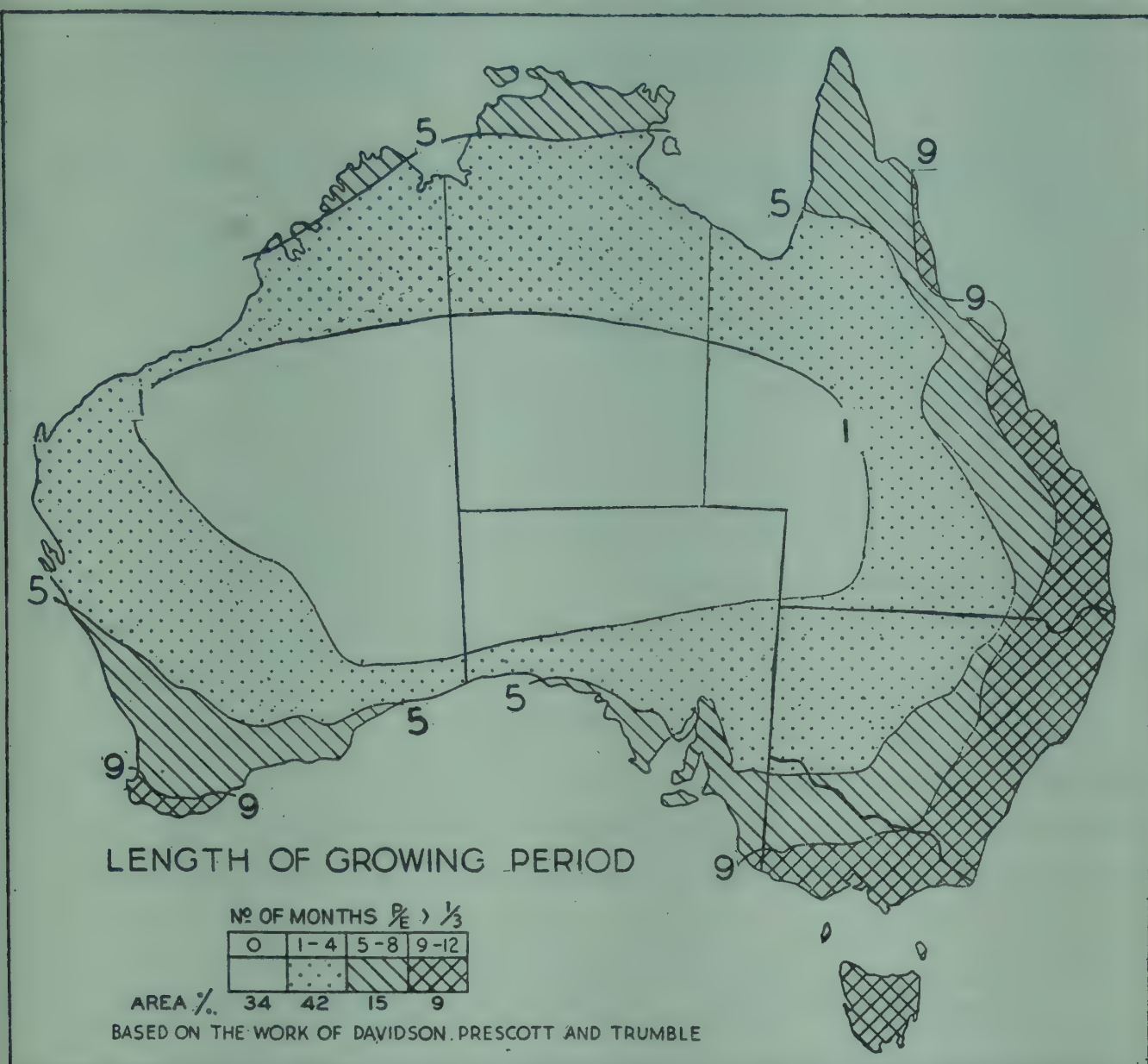


Fig. 10. Australia, length of growing period.

suspension. Unlike the truly soluble material, it is not washed right away, but is gradually filtered out in its passage, and so forms a heavier and often compacted layer in the subsoil. The resulting contrast of upper and lower horizons is sometimes so great that one might think that the upper horizon was a separate geological deposit. A few profiles are known in which this is so; a geological study shows that the mineral grains (p. 155) of successive horizons are of different origin. However, this is relatively rare. Where the upper horizon has a constant depth over a large area of undulating land, it cannot be a separate deposit.

The podzols show both of these processes of degradation. The red loams, which are likewise acid, have also lost large amounts of calcium and other elements, but have not lost clay from the surface because it is so thoroughly aggregated (see p. 78). The red-brown earths have not been leached so severely as the podzols and red loams; some soluble material has moved to the subsoil but little has been lost. The process of degradation is there, however, and these soils have already been compared to what the Russians call *degraded chernozem*.



It is surprising that the light rainfall of the Mallee should cause downward movement of clay: the reason is that the clay of Mallee soils is much more mobile (see p. 77).

While emphasis is placed here on the vertically downward effect of leaching, it must be remembered that simultaneously the clay particles move down the slope in the form of muddy suspension during rain, and this helps to make some surface soils on slopes lighter.

The contrasting zones of soils in which clay has moved are commonly called A and B, the parent material being called C. The words *eluvial* (washed out) and *illuvial* (washed into) are also used in technical writing for A and B respectively. The B horizon is not necessarily richer in nutrients than the A horizon; in the podzols it is commonly even poorer—the “illuvial” material, which makes the horizon heavy, may be of little value to plants. Each zone may be further divided. In a podzolic soil the darker surface horizon is A<sub>1</sub> the very pale lower horizon with its silica flour is A<sub>2</sub>. Again, in the red-brown, earths the upper clayey subsoil is B<sub>1</sub>, the underlying calcareous horizon is B<sub>2</sub>. In the soils of the drier climates there may be no leaching of clay, and so no B zone, but a direct passage from A to C.

#### *Climate and Leaching*

The amount of leaching in any climate depends not only on the rainfall but also on the evaporation. Annual evaporation from a free water surface exceeds rainfall everywhere in Australia except for the mountains of the south-east and a few narrow coastal strips. However, leaching still occurs during the wetter months of the year. Thus, Melbourne has 25 inches of rain and 39 inches of evaporation annually; but from May to September the rainfall is 10 inches and the evaporation 7½, and during this period some water soaks through the profile.

In Australia the effect of a given quantity of rain on the soil is far greater in the south, with predominantly winter rain, than in the north, with summer rain. No satisfactory formula has been worked out for estimating the leaching effect of the climate over the whole continent. Probably as good a relation as any is given in Fig. 10, which shows the number of months in which rainfall exceeds one-third of the evaporation from a free water surface. During such months the soil stays moist enough for the growth of shallow-rooting plants (such as subterranean clover). The two main divisions are drawn at 5 months and at 9 months. If the season of such effective rain lasts less than 5 months, the land can only be used for large stock stations. With five months of effective



rain seasonal crops may be grown, such as wheat in the south and sorghum in the north. With nine months, dairying and other intensive farming become possible.

The leached soils largely coincide with the area of 9 months growing season, which naturally includes periods of excessive rainfall. This wet crescent also includes much barren and rocky land, which serves as a water catchment only. Some leached soils also occur with a shorter growing season, especially in the north, where the wet season may be intense while it lasts. It is noticeable that many areas of better soils occur in climates that are too dry for any use except stock-raising on large stations.

The climatic map of Victoria (Fig. 11) is easier to draw for our present purpose than one of Australia. Summer rainfall here is seldom of importance, and leaching is confined to the cooler months. Rainfall for the period April to October has therefore been marked on the map. The main contrast within the state is between the north (Mallee, Wimmera, Northern District, and the adjoining North-East) with relatively low rainfall and a hot and dry summer, and the south (Western District, Central District, Gippsland) with a heavier rainfall and a less severe drought in summer and autumn. The main divide is a perfect line for separating the hot summer of the north from the milder summer of the south (the average maximum in January<sup>4</sup> is above 80° in the north, below in the south), but the line of heavier rainfall extends over the divide to include the higher country of the north, especially the mountainous North-East, where rain is very heavy. There are two dry belts in the south, one extending from the western suburbs of Melbourne through the nearer Western District, the other near Sale in Gippsland. These are associated with less leached soils (Fig. 12).

#### IRONSTONE CONCRETIONS: ONE EFFECT OF WATERLOGGING

We have several times noted "ironstone gravel" or "buckshot" in the profile. This gravel varies greatly in size, shape (round or angular), hardness, and chemical composition. Some samples contain 35 per cent of iron (50 per cent of ferric oxide), but probably the commoner value is less than half as much as this. Besides iron and oxygen, aluminium and silicon are the main constituents; many samples contain quartz or other material cemented by ferric oxide. In the great majority of cases this gravel is absent from the parent material, so it is clear that it has been formed in the soil.

Ironstone gravel occurs in soils in wet climates or in wet situations, especially above a clay horizon; it seems likely therefore that it is associated with water-

<sup>4</sup> The relation is with the climate of the soil, not of the air. However, when the air is warmer the soil is warmer also.



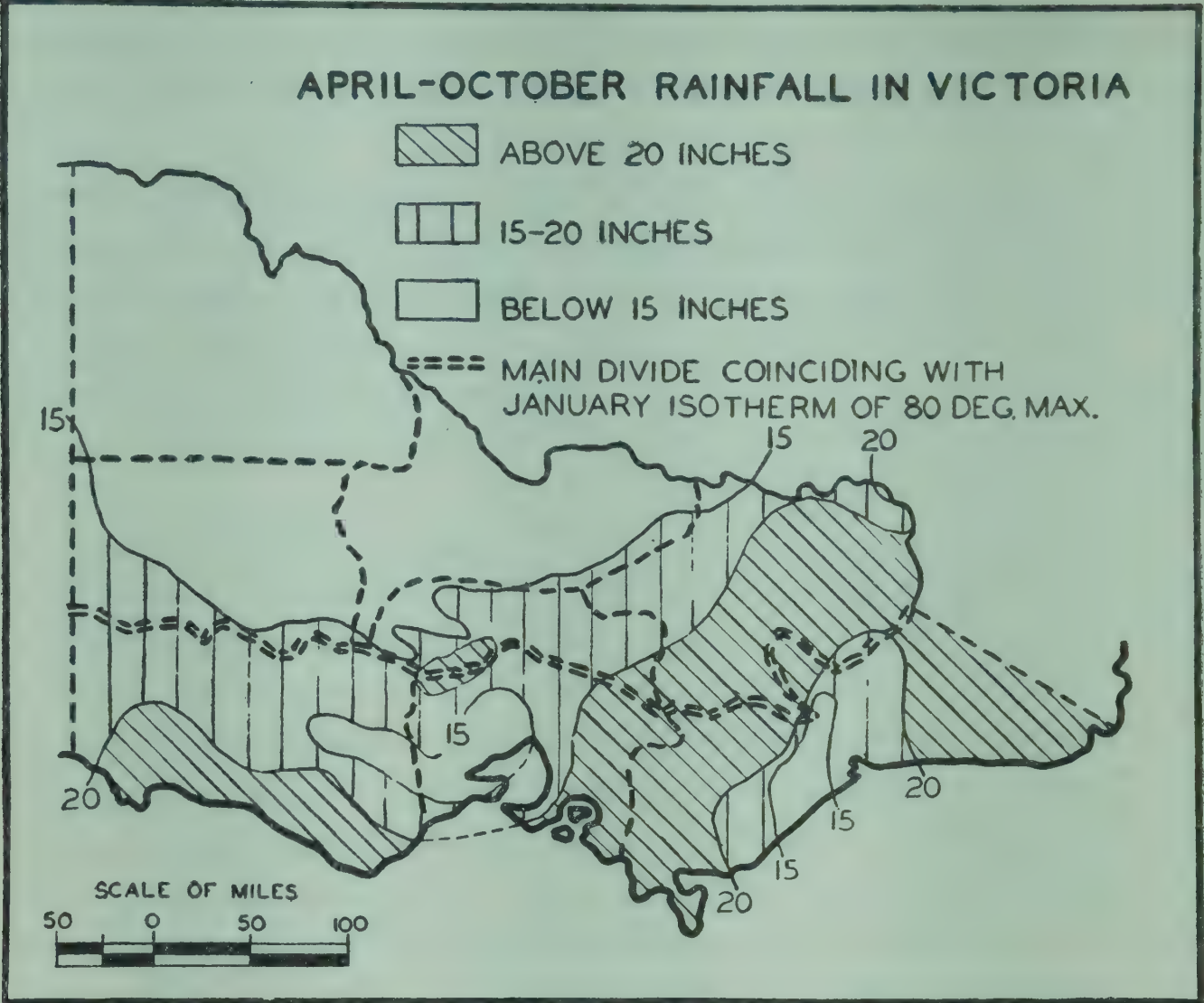


Fig. 11. April-October rainfall of Victoria.

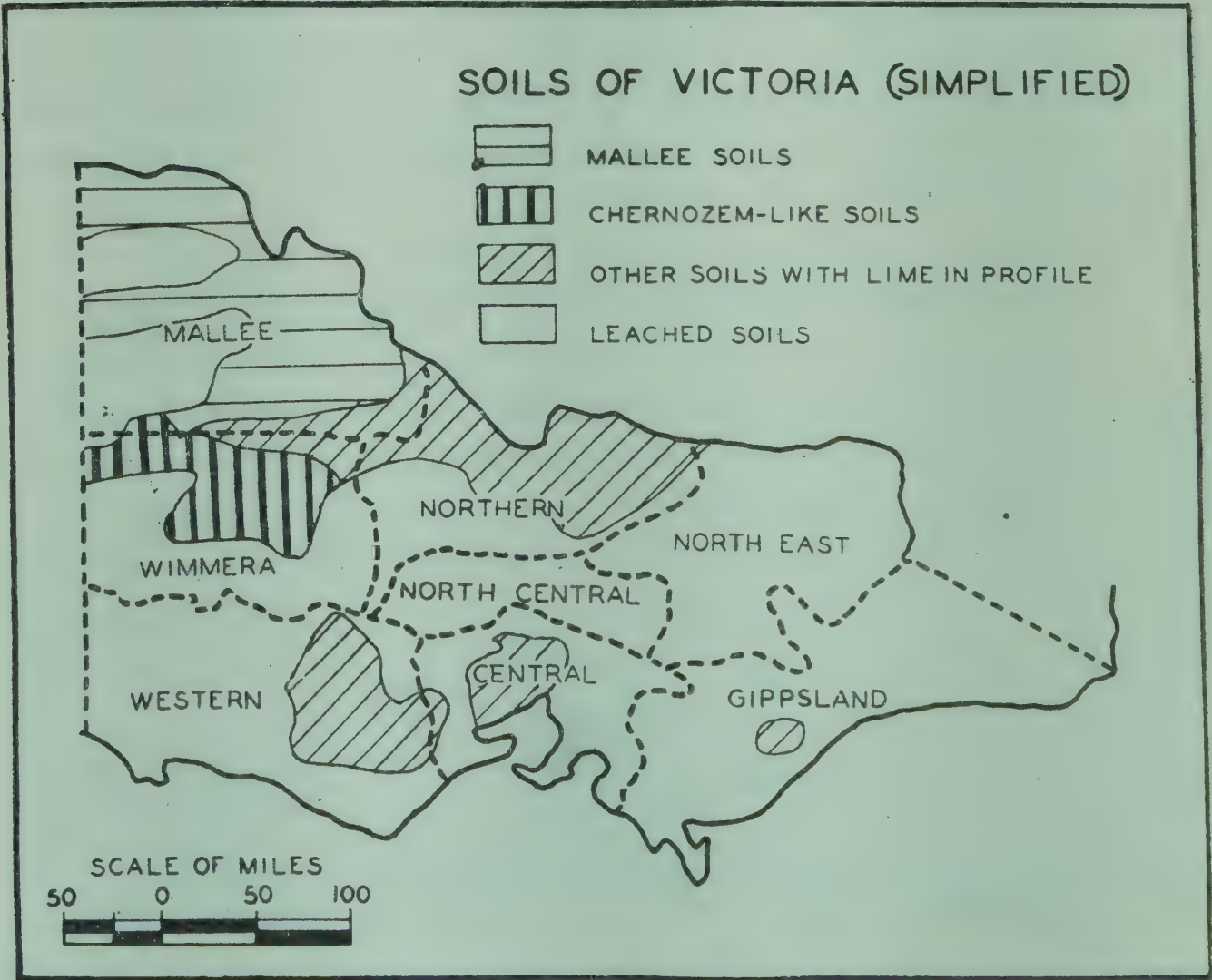


Fig. 12. Simplified soil map of Victoria. The deep sands within the Mallee district are mapped with the leached soils for the sake of simplicity.



logging. The best example of this is in some northern areas. In the Goulburn Valley, for example at Tatura, low-lying parts have a paler, greyer colour than the adjacent soil, and they contain buckshot close to the surface; the redder soil, typical of the district, contains no buckshot. The most likely explanation is that iron is reduced to the ferrous state under prolonged waterlogging in the absence of oxygen (see experiment, p. 198). During drier periods, oxygen re-enters the soil and converts the ferrous compounds into ferric oxide. For a reason that is still obscure, this oxidation happens preferentially at certain points, especially where ferric oxide is already formed. This leads to a concentration of iron into these concretions. The pale, gravelly soils of the Goulburn Valley are closer to podzols than to any other group.

Ironstone gravel is a good indicator of degradation. A soil that has been wet enough to produce much ironstone has probably also lost its reserves of necessary elements. As explained earlier, the term "laterite" is sometimes applied to this gravel. Prescott believes that Australian laterite is the former B horizon of a podzol which was formed when the rainfall was very heavy and which has lost its A horizon by erosion. Other investigators think that such gravel has always been a surface horizon, but was formed in a very wet and warm climate.

The origin of the gravel in the subsoils of krasnozems (p. 22) is obscure; it can hardly be due to waterlogging.

#### THE ROLE OF PLANTS

The destructive effect of leaching is striking, but it is only one of many factors in the formation of soils. The water that moves downwards may be lost, together with its dissolved salts; but any water in the zone of living roots can be absorbed and restored to the atmosphere by transpiration, and the ions in solution may also be absorbed and either stored in the roots or moved above ground to leaves, seeds, or other parts of the plant. When these parts of the plant die and fall to the ground, the elements thus delivered to the soil will have moved against the direction of leaching.

The more efficient a plant is at absorbing the valuable elements (calcium, magnesium, phosphorus, potassium) the more it will reduce the rate of degradation of the soil. One would therefore expect the soil to be degraded at different rates under different kinds of cover, according to the amount of inorganic matter in the foliage. Unfortunately we have hardly any information on this subject in Australia. The poverty of soils under many species of eucalypt, especially the stringybarks, suggests that these trees do little to prevent degradation. In other countries it is clear that grasses are most effective, broad-leaved trees (such as the oak) intermediate, and conifers least effective in restoring



elements to the surface. Wallaby grass and other Australian grasses, however, are not so effective, being adapted to fairly poor soils. Thus here as elsewhere the soil plays its part in determining the vegetation, which in its turn goes to determine the nature of the soil.

The most interesting example of this principle is in the province of North Auckland in the North Island of New Zealand, where kauri pine and broad-leaved trees grew together under a rainfall of 50 inches. The soil was far more strongly leached under the kauri than elsewhere; there was a well-marked A<sub>2</sub> horizon of white silica flour, which was locally called “sugar-sand”. In the rest of the forest this horizon was absent. The broad-leaved trees had kept far more calcium in circulation than the kauri and this held up the degradation. After the forest had been cleared, men searched the land for kauri gum, which was formed underground and was useful in oil varnishes. One way of recognizing the site of the former kauri was to look for the sugar-sand!

So pronounced is this upward movement, from subsoil to leaf and back to surface soil, that some elements are more concentrated at the surface than in lower layers, even under severe leaching. One example of this in Victoria is calcium, both in podzolic types and in the red loams. Howell first drew attention to this curious fact in his book on Victoria, *Soil Problems in Wheat Growing* (1911), but did not suggest the reason. (See Table 7).

TABLE 7  
HIGHER CONCENTRATION OF CALCIUM IN SURFACE OF LEACHED SOILS,  
COMPARING HOWELL’S MEAN OF 58 SAMPLES IN SOUTHERN VICTORIA  
WITH RECENT SURVEYS

	Howell Total Ca per cent	Berwick District, Exchangeable Ca per cent		
		Toomuc sandy loam (podzolic)	Hallam loam (podzolic)	Basaltic Red Loam
Surface ..	.17	.020	.11	.14
Subsoil ..	.12	{ 8-18" .010 26-46" .014	.06	{ 17-27" .07 27-39" .06

The last three soils are described in *Proc. Roy. Soc. Vic.* 52, 177-238

Phosphorus shows the same effect (p. 178), as do some of the less common elements, which have been called “biophil”, meaning that they are concentrated by living things and are therefore found in the top layers of soil and in



coal. They include manganese, zinc, molybdenum, and many others (Table 8). The view found in older books that such concentrations are due to upward movement in solution cannot be allowed.

TABLE 8  
HIGHER CONCENTRATION OF ZINC IN SURFACE UNDER LARGE TREES  
(HIBBARD, SOIL SCIENCE, 50, 54)

Depth of soil under oak tree	0-1 in.	1-3	3-5	5-11	11-17
Zinc extracted at pH 3.2 (p.p. million)	68	19	12	9	10

The total zinc in the fresh leaves was 40 p.p.m. of dry weight.

#### WEATHERING

Besides leaching, waterlogging, and vegetative growth, other influences are continually at work on the profile. The minerals in the parent rock are gradually weathering and so liberating fresh supplies of calcium, potassium, and other necessary elements. The importance of this process varies greatly with the individual profile. Naturally a rock must weather before it will form soil at all, but when a soil is in equilibrium with environment fresh weathering of the deep-lying rock is not of first importance.

The most important agent in weathering is warm water; soils of equatorial climates are commonly deep, and the fresh rock lies far below the surface, whereas the soils of northern Europe, with cool water only to weather them, have rock close to the surface, and are often high in primary minerals (see p. 156). Acidity, whether local or general, helps the process. One of the most curious items in the conventional teaching of weathering is the emphasis on frost as a weathering agent. A moment's consideration shows that frost cannot affect Australian profiles, for the simple reason that the cold does not penetrate to the depth of the parent rock!

Fine grains of feldspar and other minerals from the parent material may persist in the soil itself in appreciable amounts (see p. 157). These very slowly decompose; the mineral augite, for example, breaks up into calcium, magnesium, iron, aluminium, and silicate ions. The iron, aluminium, and silicate may recombine to form clay in that horizon (there are many clay compounds, so that no equation can be given) or one or more of these three ions may be separated and move downward. The silica flour that occurs in the upper layers of podzolic soils is probably the residue of particles that once contained aluminium and iron.



Thus a heavy horizon may be formed in place if there is some point in the profile that favours clay formation; not all heavy horizons have been formed by the concentration of clay due to downward leaching though this is very common. It may seem strange that elements should break away from a crystal like augite or feldspar only to combine again. But while the primary minerals of rocks are stable at the high temperature (1000 degrees) at which the crystals form, the secondary clay minerals are more stable at the temperature and in the environment of soil, though even clay minerals may themselves decompose.

### *What Causes Podzolic and Krasnozemic Weathering?*

In podzolic profiles silica is left in the surface and iron and aluminium are washed downwards, to be deposited again in the clay in the B horizon. Yet the red loams, which have been severely leached also, have no such concentration of silica in the surface; rocks also in their weathering become progressively poorer in silicon and richer in aluminium and iron.

No reason is known why leaching should take a different direction in podzolic soils from others. The reason commonly given in overseas books is that podzolic soils are more intensely acidic than others and are more affected by colloidal organic matter (often called "humic acid"). However, while some Australian podzols are highly acidic with a pH of 4.5 or less, many others are only moderately acidic; and a litter of organic matter is not found under the Australian eucalypt forest, as it is under the pines and other conifers of the Northern Hemisphere, where podzols are commonly found. The subject, like so many problems of soils, is still in a confused state. Meanwhile, one definite statement can be made; krasnozems tend to be formed where soils have been exposed to a wet climate for a very long time, as on old divides. Ironstone gravel also is found particularly on tablelands. Old soils in equatorial climates are particularly high in iron and aluminium.

### RESISTANCE TO LEACHING

The extent to which a profile is leached depends not only on the climate and the vegetation, but also on its relative sandiness and its original supply of calcium, magnesium and potassium. The sandier the material is, the more easily water flows through the profile and removes reserves of metals. Thus podzols extend into relatively dry climates on sandy parents. Clayey materials are more slowly impoverished; further, since fine clay cannot easily be washed in suspension through a profile which is already clayey, such parent materials do not develop A and B horizons of different degrees of heaviness unless the clay itself decomposes and forms ironstone gravel in large amounts. The



reserves of calcium and magnesium are also important. Where these are high, as on limestone or a calcareous sediment, the podzolizing process is resisted; plants demanding high calcium may grow, and so keep more calcium in circulation. Podzols still form on limestone if the slope is not pronounced, but neutral or even chernozem-like soils invade the podzol zone on sloping country, as in the Barrabool hills, near Geelong.

So long as there is a rich supply of primary minerals in a fine state of division, such as augite, biotite, and apatite, a soil is chemically rich even in a wet climate. The soils on and near the volcanoes of the Western District are a good example. In the course of centuries, however, such reserves may be liberated and washed away, and only those elements remain in the profile which are either kept in circulation or combined in very resistant forms. Most of the leached soils of Victoria have long since arrived at this state. Table 26 illustrates this point. The deeply weathered krasnozems of Nilma contain no primary mineral of the basalt from which it was derived, except for a little feldspar, which may have been wind-blown in any case. So too the less weathered profile from the buckshot plains is very poor in primary minerals. The brown loam of the Stony Rises, however, contains a good reserve of augite.

#### MATURITY

Evidently the degree to which the climate has impressed itself on the soil depends on how long the soil has remained in that climate. The idea of *maturity* has been introduced to express this relation. The red loam and the podzol, with their profiles characteristic of the district, are *mature*, while the brown stony loam of the mountains and the stony rises is *immature*. The same contrast applies to the sample from the flats at Newry (p. 25) and the surrounding podzols. The Newry soil contains good supplies of the more important elements, the podzols do not. We cannot explain this difference simply in terms of parent material; plenty of podzolic types have been formed on material laid down by rivers. It seems plain that all soils must tread the podzolic path if they remain in the climate of Gippsland, but the process takes centuries, and its effects cannot be seen on material which has been deposited by occasional floods during historical times. The term "alluvial" is used in this book, as in popular parlance, for soils of this kind, though it might be better to class them as "immature soils developed on river alluvium".

American workers have used the terms *juvenile*, *virile*, and *senile*, as well as *immature* and *mature*, to express degrees in maturity. As examples of their use, we might call the Newry soil *juvenile*, the Wimmera calcareous soil *virile* or *mature*, and the sandy podzol *senile*. However, while the idea behind these terms is good, we would get into great difficulties if we tried to



apply them generally. There is no agreement even about the scope of the word *immature*, though there is no doubt about applying it to Newry and the skeletal soils quoted.

### *The "Family"*

American workers have used the word *family* to denote a collection of profiles of different ages derived from the same parent. Thus one might find every stage of degradation from the youngest soil to the most senile. Four soil types occurring near Swan Hill, and mapped in C.S.I.R. surveys, may constitute a Victorian family, though in this case maturity has not meant degradation. Their parent material was laid down by the Murray when in flood, and presumably came from the highlands of Victoria and New South Wales. Swan Hill clay is immature, with a mean pH of 5 in the surface and 6 in the third foot—that is, the pH of a wet climate. Its heaviness does not change with depth. Two other types—Murrabit clay and Bungunyah clay—have surface pH values of 6 to 6.5 and 7 to 7.5 respectively. Beverford clay loam, the senior member of the family, has a pH above 8 and a normal increase of heaviness with depth. In this climate pH rises with time, since soluble salts accumulate to form sodium clay (p. 161); and calcareous blown dust also plays a part. Another example of the same principle occurs in North Auckland, N.Z., where the rainfall averages 5 inches a month and weathering during the warmer months is rapid. Here basalt flows of similar composition lie side by side; the soil on the younger flow is very fertile while that on the older flow has been degraded to a rather low fertility.

### *The Rate of Soil Formation*

We know little definite about the rate of soil formation in temperate climates. In equatorial climates a lava flow may weather deep enough in fifty years or so to form an agricultural soil. A good chernozem profile is recorded as being developed in Russia in 500 years. The first signs of podzolic degradation in an acid-forming forest plantation or under increased leaching may be seen in 15 to 20 years; thus, silica flour was obvious on the surface of the aggregates at a depth of 6 inches in the red-brown earth at Werribee after 20 years of irrigation which added 24 inches to the normal rainfall of 19 inches.

### *The Effect of Normal Erosion*

The normal course of erosion on a profile lying on a slope is to remove some or all of the uppermost layers. It is sometimes said, therefore, that if normal erosion is rapid enough the soil remains permanently immature. It is conceivable that soil is formed more rapidly when the parent rock is relatively close to the surface; if this is so, a profile on a steep slope may be relatively



immature and yet have a depth of as much as two feet. Possibly the immaturity of the soils of the Otway Ranges (p. 33) is partly due to this natural erosion.

Soils on level country are sometimes more degraded than those formed from the same parent material on sloping land. This contrast may sometimes be due to erosion, but is more often due to the lack of run-off from level land and the consequently wetter effective climate. In North Auckland, N.Z., the greatest degradation of soils on basalt is seen on the ironstone plateau, at a height of 1500 feet and with a rainfall of 8 inches a month. The soils on the slopes are also leached, but are very much richer than those on the plateau, with a much smaller amount of ironstone concretions.

It is interesting here to note the effect of the Ice Age in northern Europe; the ice must have scraped away the old podzolic surface, and it has left fresh rocks from which soils have been developed during the last 10,000 years which in many places are still juvenile.

At this point we may sum up the main factors in soil formation in the following scheme.

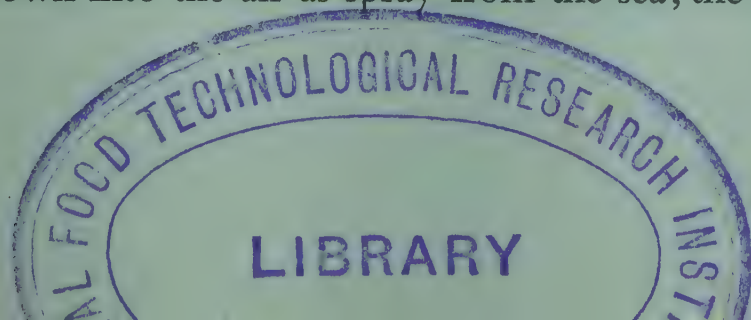
1. Leaching of soluble material into subsoil or ultimately into drainage.
2. Vertical downward movement of clay fraction to form B horizon.
3. Removal of surface material by erosion on slopes, sometimes keeping profile juvenile.
4. Deposition of mud, etc., on low-lying parts.
5. Changes due to waterlogging.
6. Restoration of elements from subsoil to surface by action of plants.
7. Weathering of parent rock and of minerals in the soil, especially by warm water.

Besides these main factors which are of general interest, two others are important in certain regions. These are, the addition of salt in the rain, and the bodily movement of the whole profile in a vertical plane.

#### RAIN AS SOURCE OF SALT IN DRIER REGIONS

Salt is common in the soils of the dry parts of southern Australia. This cannot have come from the weathering of rocks or from any geological deposit, since the rocks do not contain the necessary chlorine; it must therefore have fallen with the rain. Ample salt falls with the rain throughout the agricultural regions of Western Australia, South Australia and Victoria to add up to toxic amounts in the soil in a few tens of thousands of years, if it is not removed by leaching—and the light rainfall of inland regions is very ineffective at leaching. Thus, if rain-water contains only one part per million of salt, an annual fall of 10 inches of rain adds 1000 tons of water, containing two pounds of salt per acre; this amounts to ten tons of salt per acre every 10,000 years.

The salt is blown into the air as spray from the sea; the concentration in





the rain might therefore be expected to diminish on passing inland from the coast. Seven to ten parts of sodium chloride per million is a common concentration in southern Victoria, and one to two parts to the north of the Divide. Monsoonal falls of rain in Victoria, which are derived from moist air from remote warm oceans, are very low in salt, but the coastal showers of southern Victoria are high.

This salt from the sea is called "cyclic salt". The subject is fully discussed elsewhere.<sup>4</sup>

### "CRABHOLES"

The "crabhole" is one of the most striking natural formations of soil. "Crabholey" country has a hummocky surface, as shown in Plate VII. The pattern of the mounds and depressions varies a good deal. Some occurrences have merely a generally uneven surface, while in others the top of the mound may be three feet above the trough of the depression. We will deal here only with the examples of most practical importance—those in which the surface of the mound is calcareous and "self-mulching", and the contrast in level is marked. These occur on a large scale in the Wimmera, and on a small scale in the Western District. Similar examples occur in other parts of Australia, notably the Riverina.

The mounds are roughly circular, about three feet across, and each is separated from its neighbour by a flat depression which may be no more than 3 to 6 feet across, but in some places is much more. The surface of the mounds is calcareous; it is dark grey and "self-mulching", crumbling in dry weather into small cubical aggregates which lie loosely on the surface. The whole mound in fact, contains remarkably little soil per unit of volume. Deep, wide cracks form in the dry season; the crumbling and cracking is too violent for the roots of most plants, so that the mounds carry annual plants while the surrounding flat land carries perennials. The depressions also crack during the dry season, but not to such a high degree. The soil here is not calcareous nor self-mulching, but dries into hard clods. While the whole "complex" of mound and depression is heavy in texture, the depressions are sandier than the mounds.

The section shown in Fig. 13 was cut through a crabhole complex occurring in a basin among stony rises in the Western District. This shows that free calcium carbonate occurs at the surface of the mounds, but is two feet below the surface of the depression. The texture of these two calcareous horizons is also similar, both being very heavy when worked up with water.

<sup>4</sup> Prescott in *The Soils of Australia*, and especially V. G. Anderson, *J. Proc. Aust. Chem. Inst.* 8, 130 (1941) and 12.41, 83 (1945).





*Plate VII.* Crabhole country, Wimmera district, Victoria. Above, country with scattered puffs. Below, similar country flooded (Photos, J. S. Turner and G. W. Leeper).





*Plate VIII.* Pots of soil with good and bad structure. Above, untreated sodium soil from St. Kilda, South Australia. Below, same soil treated with calcium chloride six weeks previously (Photo, A. Walkley).



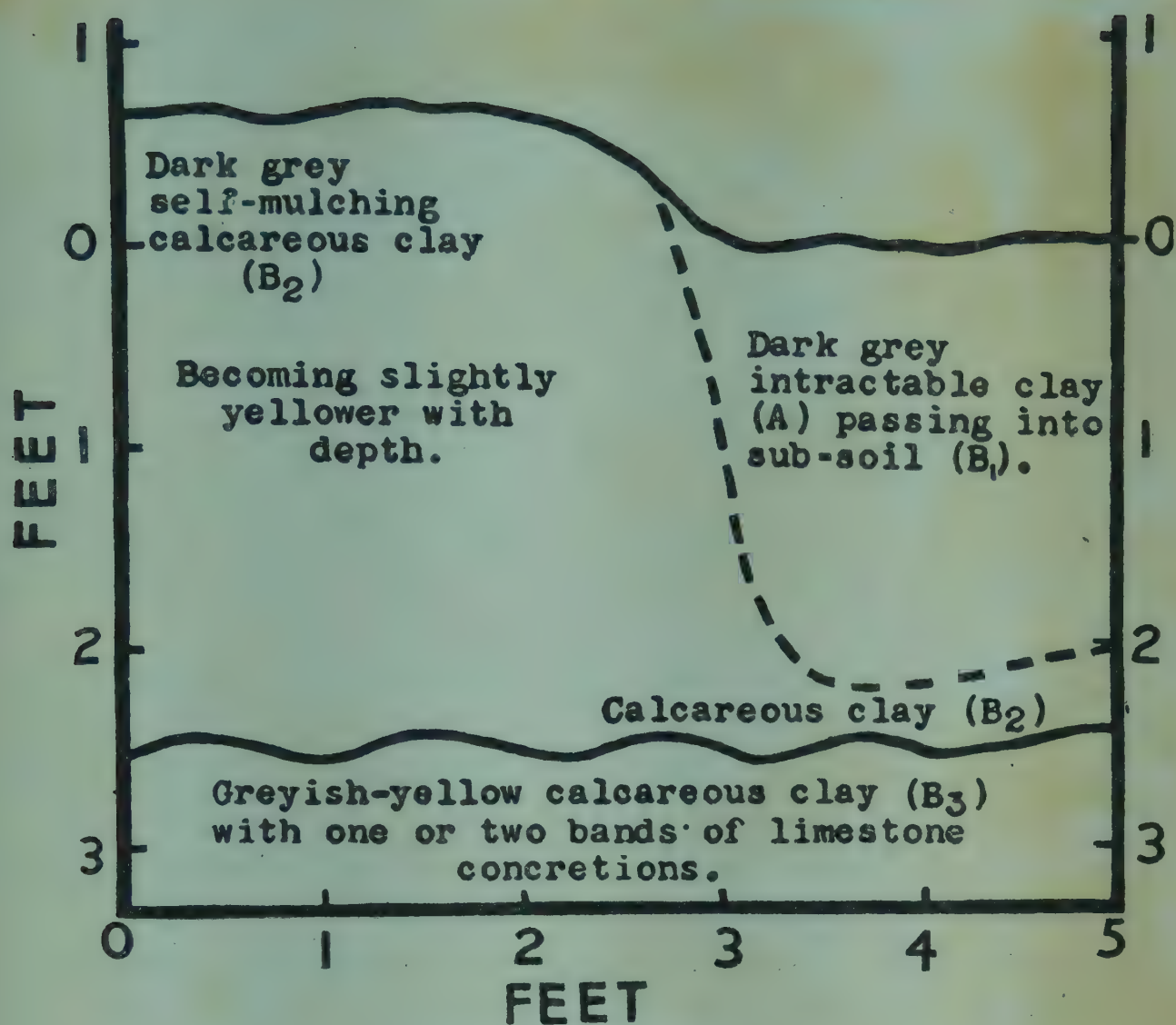


Fig. 13. Section of "Crabhole" complex.

### *Origin of "Crabholes"*

It seems likely that the mound has been formed from the calcareous subsoil. Certainly, the mound is a darker grey, but one can easily imagine the subsoil deepening in colour if it were exposed at the surface for a few years and had supported the growth of plants. If they have the same origin, there must have been a great movement of the whole soil mass upwards to form a puff, followed by removal of the surface of the puff by erosion, leaving the calcareous material—the former  $B_2$  horizon—exposed. The suggestion of a heaving of the subsoil fits in with the fact that walls of houses built on these soils have cracked on account of the movement of the subsoil.

Two conditions which are necessary for the formation of crabholes are firstly, a climate of alternating dry and wet seasons, and secondly, a clay which swells remarkably on wetting—which incidentally means that it is very siliceous (see p. 78). Both of these conditions are present in our examples. Apparently, something like this happens: When the soil dries and cracks in summer, pieces of the surface fall down the cracks, adding to the bulk of



material below. When this becomes wet again, it swells, and so exerts additional pressure upwards and sideways. The pressure is relieved at a point of weakness to form a puff. The pattern of points or lines of weakness determines the pattern of the final crabhole system. Crabhole country has been levelled and cultivated in many places, so that the crumbly calcareous surface becomes more widely distributed. Even after levelling, however, the puffs can form again if the land is left under grass, since the process of cracking, mixing, and swelling must go on.

Thus the popular term "crabhole", with its suggestion that the depressions have been hollowed out or have sunk, lays emphasis on the wrong half of the system. The Americans have invented the term "hog-wallow" for what seems to be a similar formation. The aboriginal name *gilgai* sounds less absurd than the others, but this word is not used in Victoria.

The vegetation of the complex would make an interesting study for a botanist. The association of annual plants with the puffs has been mentioned. Another curious association is that of the burr medick, which was the only plant found on some puffs in the Mt. Gellibrand area of the Western District. This burr grows only in the crabholey country in this area—possibly on account of its preference for high pH, since only the crabholey land is alkaline—and consequently the wool from the crabholey paddocks has to be kept separate from that of the rest of the station.

*Original Surface of the Wimmera "Self-mulching" Types.* It is not known how much of the cultivated "black" Wimmera land was originally crabholey. The self-mulching land is certainly closely related to the crabholey land, as is shown by the way in which the calcareous horizon in the subsoil fluctuates in level. However, the surface may have been uniformly calcareous before settlement in some parts.

The crabholey land still lying under grass or woodland (as between Glenorchy and Rupanyup) is either liable to flooding, or locally believed to be inferior and too difficult to work, probably on account of its lower content of lime. Many mounds in the Wimmera are dark brown rather than grey.

*Other Crabholey Types.* The term "crabholey" is given to all undulating clayey surfaces, whether the tops are calcareous or not. The reason for giving so much attention to the calcareous variety here is that it is such a curious case of soil formation. Clearly any clay subject to alternate cracking and swelling must form an irregular surface. An acidic type occurs on the Buckshot Plains (p. 19), where the depressions have grey silty loam with up to six inches of buckshot overlying clay, while the hummocks have yellow clay at or close to the surface.



## THE EFFECT OF ANIMALS ON THE SOIL

(a) *Man*. Man has had a tremendous effect on soils. Here are some of the most important of his actions. By cultivating and by stocking the land heavily with grazing animals he has exposed the soil to erosion. Again on the debit side, he has robbed some soils of their fertility and in particular has spoilt the originally good structure by intensive cultivation. On the credit side, sowing subterranean clover has led to an improvement in the structure of some originally poor soils apparently through the different quality of the organic matter produced. Heavy doses of lime, such as were common in England in earlier generations, can change the direction of soil formation for centuries. Irrigation also has far-reaching effects; it may leach valuable elements from the surface—which appears to have happened with potassium at Werribee—or may lead to the accumulation of salt near the surface. Consider also the effect on the profile caused by artificial drainage. Many soils of Holland are largely man-made; where land reclaimed from the Zuider Zee consisted of sand overlying clay, some subsoil clay was mixed with the sandy surface using huge specially-designed machines, in a similar way to the “trenching” of the town gardener, though on a greater scale.

(b) *Rabbits, Yabbies, Termites*. These animals living in the soil can move large masses of it. The burrowing of rabbits and yabbies clearly upsets any profiles, and the rabbit may also cause erosion by destroying plants. The termite is the most interesting of this group. Old termite burrows at Griffith (N.S.W.) provide tracks for the roots of trees in otherwise impermeable subsoil. Some tropical areas are thickly studded with termite mounds, which may differ markedly from the surrounding land. This is due to several factors; the mounds may be built of material selected by the termites as some ants select gravel; the mounds are much warmer and drier than the surrounding land—which may be reflected in a redder colour; and the mound contains not only the organic residues of the termites' food, but the accumulated metals such as calcium derived from food from the surrounding land. In parts of Siam the termite nests are islands of fertility in severely leached ironstone country, and the inhabitants plant their vegetable gardens on these nests. Such mound-building termites are not so important in temperate Australia, but similar islands of higher fertility have been noted in the ironstone country of Western Australia on the site of old ant-nests.

(c) *Earthworms*. Worms pass soil through their bodies as they travel; in this way they mix neighbouring layers and leave relatively loosely-packed material in their tracks. English writers consider both of these processes very important, but we do not know whether they are so important here. At the



famous experimental station at Rothamsted there is a field which has not been ploughed for 300 years, and on which there is a horizon of nine inches of fine brown loam overlying a layer containing flints, which are two inches or so across. Such flinty layers are seen today on the neighboring ploughed land, so it is reasonable to suppose that this was the former surface. The overlying nine inches has presumably been brought up by the worms, which naturally can only move fine material. There is no evidence of any such work by Australian worms; neither does there seem to be any evidence that Australian worms need a neutral or calcareous soil for their health, as has been stated for English worms.

### COLOURS OF SOILS

The ordinary person naturally distinguishes soils by their colour. The deeper colours—red, brown, dark grey, black—are widely regarded as a sign of greater fertility than the lighter greys and yellowish tints. Thus a poor, light grey soil gives a much more favourable impression if seen immediately after rain. The preference for deep colours is generally sound. There are, however, many exceptions, some black soils and many red soils being infertile.

Colour is used also as a basis in scientific classification. This has been carried much too far. Many descriptions of colours are mere personal impressions; the impression depends on the wetness of the soil, the time of day and the position of the sun. In any case, two soil types which are distinguished from each other in colour may be essentially the same in relation to the growth of plants. However, colour often has an interesting relation both to fertility and to soil formation.

#### *Origin of Colours*

*Black.* Blackness is usually associated with richness in organic matter. However, the pigment which causes dark tints is only a by-product of bacterial action, and depends on the nature of the organic matter rather than its total amount. For example, the "black" soils of the Wimmera contain less than half as much organic matter as the pale grey podzolic soils to the east of Melbourne. Generally organic matter is paler in acid than in neutral environments. The reason why black is a good sign is not that it means a great deal of organic matter, but that it means probably that the soil has not been impoverished and contains plenty of calcium.

*Red and brown.* Red tints are due to iron, as is generally known. However, red soils are not necessarily high in iron, and plenty of soils contain a lot of iron and are grey or yellow or black. The red is due to free ferric oxide, which is a strong pigment. This may mingle with organic pigment to form a brown or chocolate, or it may dominate the colour even where the organic content is high. This may be selectively extracted (see appendix) leaving a grey or brownish



grey residue. Many, though not all, yellow soils when similarly treated lose little iron and retain their yellow colour. In such soils the iron is present in firm combination with silica; the yellow mineral nontronite ( $3\text{SiO}_2 \cdot \text{Fe}_2\text{O}_3 \cdot n\text{H}_2\text{O}$ ) is known to occur in the clay fraction of such soils. There is, of course, nothing in this difference to indicate a higher fertility in red than in yellow soils. However, the "Red Loams" (such as those of Kinglake and Lismore, N.S.W.) have a desirable granular structure which is partly due to the free ferric oxide. This allows them to be well-drained, which is particularly important with a rainfall of 40 or 50 inches. There is little doubt that much of the prestige of red soils is due to their common occurrence on high land where rainfall is ample.

It might be added here that the health of fat lambs in northern Victoria is not connected with the iron in the soil, conspicuous as the red colour is on their wool.

In many districts away from the coast, the soil on hills or slopes have red tints while those on the flats are grey. This absence of colour on the flats is not connected with any reduction of iron to the ferrous condition (which calls for severe waterlogging) but is due to the much greater amount of silica in the clay. Generally speaking, grey clays have a molecular ratio of silica to ferric oxide of 4 or more, coloured clays have a ratio below 4.

We are not sure what conditions are needed to produce this red pigment; it is formed both in warm, wet climates and in regions of summer drought. Once developed it is very persistent, but it disappears from surface soils under waterlogging. A yellow tint may indicate simply that the environment has never been favourable for producing a red. Yellow tints are especially common in the heavy subsoils of podzolic types.

### *Mottling*

Many subsoil horizons are mottled, the commonest pattern being red-yellow-grey. Pronounced mottling is associated with periodical waterlogging. The red zones occur along root tracks—that is, in the driest parts of the horizon. No one seems to have studied this problem, but perhaps here too the red once formed is stable for a long time. Possibly a red tint is even more stable in a leached subsoil at a depth of four feet or so than it is at the surface; it seems that the anaerobic bacteria which can destroy the red by reduction (see p. 198) need both organic matter and calcium, both of which are in far better supply at the surface.

In making a mole drain through a subsoil (p. 105) it is essential that the horizon used must not be naturally well aerated, or the mole will dry and crack too easily. Faint mottling with grey as a conspicuous colour shows that the horizon is suitable; a uniform bright colour, the reverse.



## OLDER WAYS OF MAPPING SOIL

Two common ways of mapping soil are according to parent rock and according to native vegetation. These methods are less satisfactory than the study of the actual profile; their chief merit is that they save the mapper's time.

I. *According to Native Vegetation*

Land is commonly described locally by the vegetation which it originally carried; in some places the name persists even after all the native timber has disappeared. Thus in the hills of South Gippsland, which now carry either grass or bracken, "bluegum" country has a better reputation than "messmate"; and in the Wimmera there is "buloke" and "plains" (i.e. originally treeless) country.

It was natural that people should classify country in this way. Differences in vegetation strike the eye, and the first settlers recognized that some trees indicated a good soil, others a mediocre or poor soil. The tall, straight blue gum on better land contrasts with the straggly peppermint on adjoining poor land, as for example at Nyora (S. Gippsland). At the other end of the scale, the grass-tree and the "honeysuckle" tree indicate sandy country of very low fertility. Another good correlation of trees with soil is on sand-ridges in the Mallee, where pure stands of Murray pine are associated with deep sand to sandy loam which grows good oranges under irrigation. It would be dangerous, however, to argue that if native trees grow tall, crops will also. The tall and valuable jarrah forests of Western Australia, and the ironbarks of Victoria grow on very poor soil, as did much of the kauri pine of New Zealand.

One should know as much as possible about these relations of native plants to soil; but a mere map of vegetation is only a makeshift for a proper soil map. Vegetation is due to climate and to other factors besides soil, and in any case it does not give enough information. A piece of land may appear uniform and may carry the same trees throughout, but may consist of three or four distinctive soil types which will show their differences as soon as the land is put under crop. Red gum has occupied thousands of square miles in the far Western District, in which there is a great diversity of soils.

Those who rely on vegetation may even come to false conclusions. The most important example of this is seen in the equatorial forests; where the climate is ideal for growth, dense forests may develop on soil that is chemically poor. As soon as the forest is burnt, all the reserves are concentrated in the ashes; the first few crops may be excellent—but yields fall off rapidly, since the chemical reserves of the soil were low. This experience has often been repeated in equatorial countries, and has some application to the krasnozems of the east and south-east of Australia, especially in the subtropical and tropical plateaux



from Dorriggo to Atherton. Again, the swamp tea-tree, which grows in wet places in Gippsland, has often been taken to indicate country of higher fertility than the average. However, it is simply a sign of wetness, and not of good soil, and though the soil in the depressions which carry this tea-tree may be heavier than the surrounding land, it may also be sandy. As a further example, graziers in North-East Victoria say that land carrying peppermint is "sour"—a popular term which means no more than "poor". Certainly the peppermint grows on some soils that are poor in nutrients; but in the mountains around Omeo it grows on soil that is as deep and appears to be in every way as good as adjacent land under white gum or snow gum. It may be that the grass under the peppermints is inferior to that under the other eucalypts, but there is no evidence that the soil is any poorer.

## 2. *According to Parent Rock*

A soil must be related to the rock or sediment from which it was derived. Quartz sand cannot form clay, nor vice versa. However, a soil is not just decomposed rock, with perhaps a little humus on top; it has had a history, as has just been explained. Mapping by parent rock has survived in this country because of the prestige of English textbooks. But it is fallacious, as can best be seen by taking three Victorian examples.

(a) "*Silurian soil*". Silurian rock, largely mudstone, is the parent material over a large area east and north-east of Melbourne. The soil developed on gentle slopes is podzolic, with a grey silty loam on the surface—similar to Hallam loam. This type is sometimes called "Silurian soil". Now there may be some excuse for this name so long as everyone knows what is meant, namely, "The soil developed on gentle slopes on Silurian mudstone in Central Victoria, consisting of a light grey silty loam overlying a yellow clay at 17 inches, and uniformly acidic and low in nutrients". But only people who are familiar with the Central District of Victoria can know what is meant; a citizen of Mildura or Hobart would be left in the dark. There are all kinds of Silurian rock in the world, and all kinds of soil are formed on them—including, incidentally, the deep red loam of Kinglake, which has just as much right to the term "Silurian soil" as its podzolic neighbours have. So though the term may be understood by a small select circle, it is better to avoid it.

(b) "*Tertiary sand*". This might mean (i) a podzol, thoroughly leached and acidic, or (ii) a Mallee soil with  $\text{CaCO}_3$  in the subsoil. Even the first interpretation is highly ambiguous, since the profile might be deep sand, or sand over a clay subsoil.



(c) "*Basaltic (or "volcanic") soil*". The soils formed on basaltic lava in Victoria include:—

- (i) Red loams, acid throughout, and deep (Warragul, Trentham).
- (ii) Red-brown earths (Werribee).
- (iii) Grey clays (Cressy).
- (iv) Calcareous, self-mulching (Natte Yallock, Mt. Gellibrand).
- (v) Black and acidic (Berwick).
- (vi) Buckshot podzols (Moyne Falls).
- (vii) Brown stony loams, immature.

The term "basaltic soil" is therefore meaningless. "Volcanic soil" is no better, even if confined to truly volcanic material. It might mean the poor material derived from pumice showers in the North Island of New Zealand, and it might just as well mean the immature soil formed on basaltic tuff, which occurs at Koroit and Mt. Gambier. In fact its use is even worse than this, being extended to numbers of rich soils in Victoria. In New Zealand there has even been invented a new term, "semi-volcanic"!

It is clear that a general classification in geological terms is useless. This, however, does not mean that the nature of the parent rock does not matter. In fact, the soil type normally changes wherever the parent rock changes and a geological map is essential for soil mapping. Within a small region of a few hundred square miles, it may be justifiable to refer to the "granite soil" and the "basalt soils" if we are sure there is no ambiguity; but such terms must be confined to local use.

The question is sometimes asked, "Which is more important in forming soils, climate or geology?" There is no general answer to this question, any more than there is to the similar question applied to human beings, "Which is more important, heredity or environment?" There are many examples of young alluvial types where climate has had no effect. There are also many examples where severe leaching has obliterated any trace of difference between soils developed on different rocks. But the question is an unprofitable one. Nowadays we look for the marks of both heredity and environment in each profile that we study, and recognize that a number of complex factors have led to the product which we observe. The parent material of the Victorian Mallee, for instance, must have been highly calcareous; the calcareous nodules in the subsoil, however, owe their situation to the environment.

### *"Sedentary" and "Transported" Soils*

A distinction was formerly made between "sedentary" soils, which are developed directly from the underlying rock, and "transported" soils, the upper horizons of which have been washed down from higher levels. The purpose of this distinction is obscure. In any case, a *soil* cannot be transported,



since every horizon of a soil bears a historical relation to every other. Once a soil is moved by wind or water, it becomes only *soil material*, until it is again fixed by vegetation, when it can become *soil* again. A sedentary soil may be deep, shallow, immature or severely leached. A transported soil likewise may be deep, shallow, immature or severely leached. In short, this old classification has no practical value.

#### SOILS AND HISTORY

A soil profile is the result of thousands of years of interactions of rock, climate, and living things. We can expect to find in it some relics of its past. The charcoal left by the original forest on our podzolic types is the most obvious example, but there are others which are less obvious.

Three examples may be given of the effect of past treatment, two of which are archaeological. Firstly, the sites of neolithic settlements in Sweden have been indicated by abnormally high concentrations of phosphate in the soil. Secondly, the prehistoric road from the river Avon to Stonehenge in England was identified from the air by the fact that barley made poorer growth on this compacted strip. The other example refers to more recent times, and shows the result of earthworms in building a layer of fine earth over a stony surface (p. 56).

Other examples relate to past climate. The outstanding cases are soils which now live in a dry climate, but which are acidic and degraded, and have evidently been formed in a previous wet climate. Both in Western Australia and inland Queensland there are huge areas of infertile gravelly soils which were formed when the climate was much wetter and are very different from the "pedocals" which are produced where the old gravelly surface has been eroded away. White silica flour may tell a similar story (p. 46).

A curious case of the opposite sequence is in England, where red soils are formed on a geological formation called the Old Red Sandstone. Here the redness is due to the desert climate at the time the sandstone was formed. The wetter climate of today has not affected the colour, which is chemically very stable.







PART II  
THE PHYSICS OF SOIL







## CHAPTER IV

### INTRODUCTION TO PHYSICAL PROPERTIES

#### PHYSICAL PROPERTIES OBSERVED IN FIELD

THE PHYSICS OF SOIL IS JUST AS IMPORTANT AS ITS CHEMISTRY. MOST CHEMICAL shortcomings may be made good by simply adding the necessary fertilizer; but no amount of nutrient will make up for poor physical properties. By these properties we mean mechanical behaviour when wet and when dry, the things we observe particularly in a cropped or cultivated paddock. If the land is dry, we note the size and hardness of the lumps on the surface, whether they are crumbly or not, whether the surface is cracked, how wide any cracks are—or perhaps whether the soil is so sandy that there are no lumps but only individual sand grains. If rain has fallen recently, one soil type may be passable and fit to be worked while its neighbour is still sticky or may have water still lying on the surface. As an extreme case, a soil when wet may lose all its mechanical strength and become like a quicksand. This state is called “spewy” and is commonly found in podzolic types under poor native pasture where a permeable surface overlies a heavy subsoil. The ideal soil can be worked soon after rain and also does not become too tough to work as it dries. Sandy soils, though not otherwise ideal, have these advantages; other soils, including the krasnozems, also have them while they may otherwise differ from sandy soils. Some soils pack tight after being beaten down by rain, and set with a hard crust on drying. These are found in every district (e.g. Rutherglen, p. 68). In some districts there are soil types that are “scoured” or eroded by water more easily than others. In a dry district there may be a corresponding problem of the liability to blow. Thus the loose sandhill in the Mallee may blow easily; but the self-mulching types of the Wimmera may also blow if they are in a fine powdery state.

Some of these physical properties are easy to reproduce in small pots or plots. A soil which is packed by the rain may be compared in pots with the same soil treated with gypsum (which improves its behaviour more effectively than lime). In the field the treated soil is drier during a wet spell, the contrast being visible fifty yards away. Again, treating a soil with sodium carbonate at the rate of a pound to the square yard produces the bad property of setting to a massive state; the treated soil is rubbery when moist and hard when dry.

Here is a set of facts facing the scientist, and here as elsewhere there are the three stages of measuring, explaining, and controlling. In some cases we can control physical properties, the best example being the effect of gypsum in increasing permeability. But to a large extent we are still only measuring the



things which farmers have long observed in a qualitative way. The following paragraphs give a few such measurements.

### (1) *Rate of Absorbing Water*

A cylinder is driven in to the desired depth, and water added from on top, so that the head is as nearly constant as possible. The time is recorded for each inch of water or fraction thereof to disappear. Fig. 14 shows the behaviour

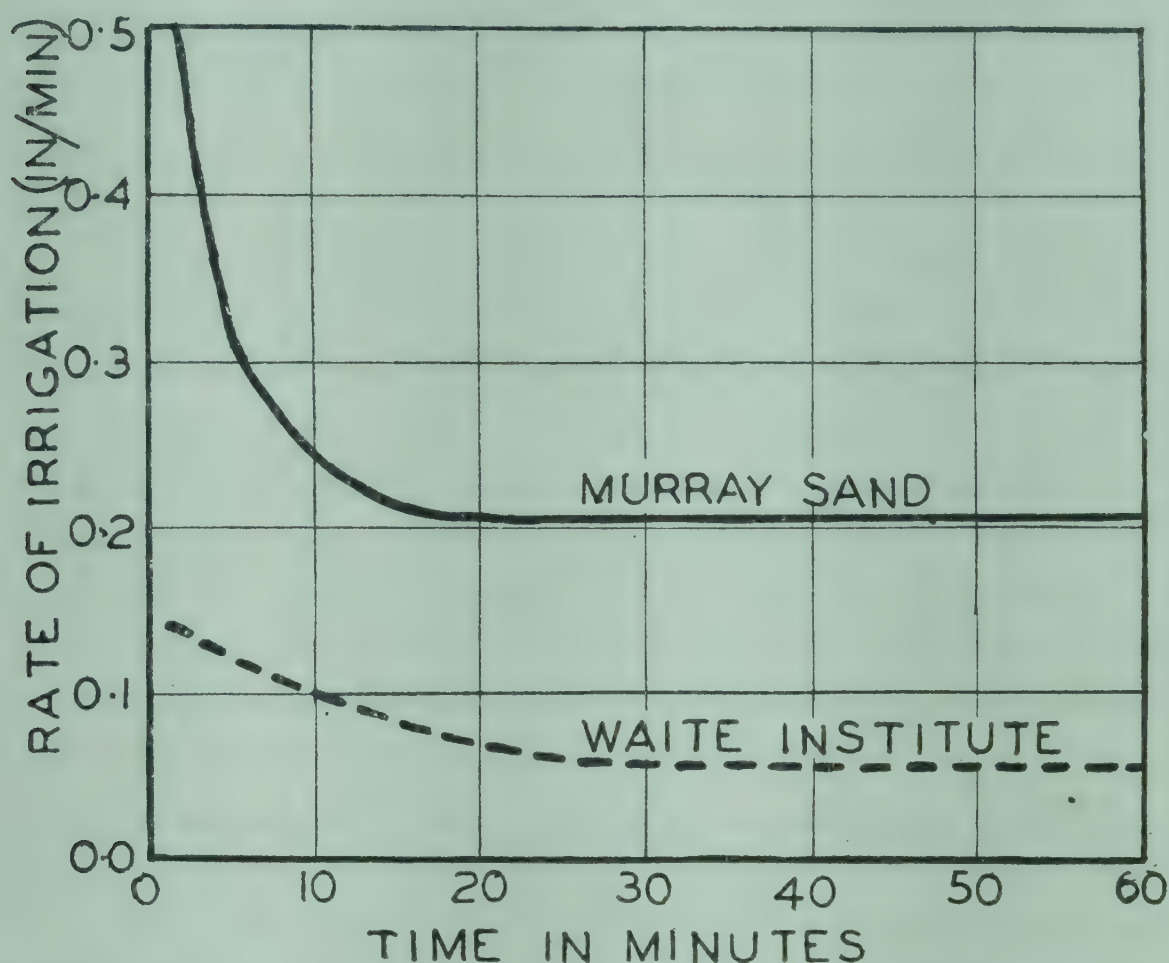


Fig. 14. Rate of penetration of water into two soil types (after T. J. Marshall, Waite Institute).

of two contrasting types. As the experiment goes on, water penetrates more and more slowly, partly because when a foot or so is wetted the moisture gradient in that surface foot becomes low, partly because a heavy soil gradually swells and its channels close. In wet regions, such studies are of interest in indicating how big a fall of rain will cause run-off; in irrigated regions (where most Australian work has been done) the problem is, how readily a given type will take irrigation water, which is applied more rapidly than rain is likely to fall.

### (2) *Structure and Tilth*

The condition of small or large lumps or a self-mulching layer on the surface is called tilth. This is one aspect of the *structure* of a soil. We have already seen that soils are classified in terms of *texture*—that is, the feel in the hand when



a lump is crushed and worked up to a moist state with water. Texture is very important, but in the course of determining it by crushing and kneading the lump we have destroyed structure, which is the arrangement of particles to form compound units. The simplest measurement of the tilth of a field is the percentage of lumps passing sieves of various sizes— $\frac{1}{2}$  inch, 1 inch, and so on. Thus Table 9 shows some English results. After a wet winter without freezing periods the bare soil under constant beating by the rain has run together to form large lumps, which have to be broken down by further cultivation before

TABLE 9  
EFFECT OF WEATHER AND DRASTIC CULTIVATION ON TILTH

	Percentage of Clods above $1\frac{1}{2}$ " in ploughed layer	
	Before cultivation	After cultivation
After "hard" winter ..	11	2
After wet winter ..	60	14

the land is anything like fine enough for sowing. After a "hard" winter, with dry freezing spells, the lumps are as small before cultivation as they are in the other season after cultivation. This distribution of clod-size can be measured easily with scales and a set of sieves. The method can be used to compare one cultivating implement with another; the more drastic implement will leave a smaller number of large clods.

### (3) *Apparent Specific Gravity*

The specific gravity of the solid particles of soil—sand grains, for example—is close to 2.6. A block of soil taken from the field, however, is less dense than this, and its *apparent specific gravity*—the weight in grams of 1 cc., after subtracting all the water present—may be only half this value, since the volume of the block consists largely of air. This apparent specific gravity (which is sometimes called the *volume weight*) evidently indicates the looseness or compaction of the soil. Its value may lie between 1.3 and 1.6 for a difficult surface soil, and from 1.0 to 1.2 for one that is easily worked, though sands also reach a value of 1.6. The space not accounted for by the solid grains is called *pore space*. This space may be occupied by either air or water; both its total amount and the distribution of air and water are important properties, which are dealt with in more detail later.

Two other measurable properties of soil in the field may be quoted here. One is the force required to pull a plough through the soil; the machine on



which this is recorded is called a dynamometer. Using a similar mouldboard plough, and working with the soil in its most favourable condition, the chernozem-like soils of the Wimmera require a pull of only 4 pounds per square inch and the krasnozem of Mornington Peninsula  $5\frac{1}{2}$ , while the difficult red clay loam of the Werribee plains requires 15. Another property, the degree of compaction, can be measured by the number of blows of given weight required to drive a spike 12 or 18 inches down.

#### WATER-STABLE STRUCTURE

Besides these measurements in the field, some simple laboratory methods can measure the *likelihood* that any soil will pack hard or become cloddy after rain. These effects are due to the filling up of spaces in the soil by fine material. If the soil contains aggregates of a fair size which keep their shape and do not melt into muddy suspensions in wet spells, it will not pack. So we can measure the percentage of *water-stable aggregates* above a certain size by putting a sample of 20 or 25 grams of soil through sieves under water (p. 201). In this way any aggregate which would fall apart and turn into mud in the field will pass through the sieves. "Crumbs", as the stable aggregates are called, are easily recognized in the field. It seems that the best relation to field behaviour is given by the percentage of stable aggregates above  $\frac{1}{4}$  mm. as is exemplified by the soils listed in Table 10. The soil from Rutherglen has a poor structure and is typical of those that pack hard; many orchard soils of the Goulburn Valley are similar. Cashel clay and Kerikeri clay both have excellent natural structure,

TABLE 10  
WATER-STABLE AGGREGATES ABOVE  $\frac{1}{4}$  MM.

Soil		Per cent organic carbon	Per cent aggregates above $\frac{1}{4}$ mm. in soil
Sandy loam, Rutherglen (Podzolic with ironstone) ..	Long cultivated for cereals, hard packing	1.0	12
Do.	Cultivated after 8 years clover	1.7	53
Cashel clay, Dookie (Chernozem-like) ..	Long cultivated for wheat	—	40
Kerikeri clay (N.Z.) (Krasnozem) .. ..	Long cultivated orchard	4.2	92





*Plate IX.* A naturally good-structured soil: black soil on much-weathered basalt, Berwick, Victoria. (Photo, B. A. Pearl).





*Plate X.* Profile affected by deposits from recent erosion. Upper foot consists of loose brown deposit. Below is the original surface ( $A_1$ ) and sub-surface ( $A_2$ ) of a podzol profile, succeeded by clay subsoil (B) showing extensive cracking.



and keep this for a long time under cultivation. A long period under subterranean clover temporarily raises the Rutherglen soil to the desirable level of Cashel clay.

#### POT AND LABORATORY WORK

This test raises two questions; firstly, how far can we rely on any results obtained with soil removed from its natural situation, and secondly, how can we take a sample of 20 grams of soil that will represent a whole plot of land? Regarding the first question, it is obvious that for many investigations we have to move the soil into the greenhouse or the laboratory.

(a) *Pot tests* may be used to determine the soil's behaviour both physically (towards air and water) and chemically. They may give valuable information about the soil's chemical behaviour, but their results must be treated with caution, not only in chemical but still more in physical problems. In the process of moving the soil we destroy its natural state, which has been developed over hundreds of years. Pot tests usually differ from field work in being carried out on the surface soil alone, but even if the subsoil is included the result may still be misleading. It is no good to take a pot three feet deep and dump in two feet of subsoil and then one foot of surface soil on top. All the channels that were in the natural profile have been destroyed. Plants growing in the pot may find it easier or harder to use the subsoil than they would in the field. The difference may be too great for us to rely on the pot test. Some chemical tests with pots even involve mixing the soil with its own weight of sand in order to avoid any of these physical complications.

(b) *Laboratory tests* are also indispensable, but they too have the disadvantage involved in destroying the natural arrangement. This applies particularly to the "fine earth", which is the material used for almost all analyses other than structure. This is prepared by allowing the sample of soil to dry in the air and then grinding it by hand with a wooden block (mechanical grinding breaks down the coarser particles), and separating the material which will not pass a 2 mm. sieve. This coarse material, consisting of gravel with some sticks and roots, is commonly ignored in analytical work, though its weight should be noted (this is often less than 1 per cent of the total). All that passes the sieve is known as the "fine earth". The limitation of "fine earth" is obvious in physical work, but it is also important chemically. The inside of an aggregate of soil has a different chemistry from the outside, and information may be lost when the two are ground together.

(c) *Sampling*: Soil is variable and a sample taken at one point may give different analytical figures from one taken a yard away. A worker who wants to find whether two areas of soil are really different analytically must therefore



take several samples of each soil and apply statistical theory to his results. Failing this, the best procedure is to take a large bulk of material, mix it and spread it out evenly in the shape of a circle, take a subsample from alternate quadrants, and then keep on subsampling until the residue is of about the required size—10 grams or whatever it may be. Fine earth must always be subsampled in this way, since it segregates into large and small grains when poured from one vessel to another.

#### EXPLANATION OF STRUCTURE

All the figures obtained in structure analysis can give useful information as to whether some treatment has had any effect, as compared with a personal impression which may be wrong. The next stage, that of explaining our observations, involves some knowledge of the very fine material of the soil, namely, *colloids*. These will be dealt with in the next chapter.



## CHAPTER V

### COLLOIDS OF THE SOIL

THIS CHAPTER GIVES AN ACCOUNT OF THE NATURE OF COLLOIDAL MATTER, which plays such an important part in the physics and chemistry of soils. Naturally such a book as this can give only a short and simplified account of colloids—enough to form a foundation for the discussion in later chapters. There are many books which deal at greater length with the more complex aspects of the subject that are omitted here; *Colloids* by Hedges is particularly useful for the less advanced reader.

Colloidal particles are defined in terms of size, which is responsible for their characteristic properties. It is convenient here to use as unit the millimicron ( $m\mu$ )<sup>1</sup>—that is, the millionth part of a millimetre or the thousandth part of a micron ( $\mu$ ). A millimicron is 10 times the Angstrom Unit (A.U.), which is used for recording dimensions of atoms. Colloidal particles are usually defined as having diameters between 2  $m\mu$  and 200  $m\mu$ , that is, they are larger than ordinary molecules like sucrose, but too small to be seen under a microscope. On account of their small size they are notable in two ways—firstly for their large area of surface relative to mass, and secondly for their ability to form stable suspensions. The first property may best be shown by a numerical example.

#### SURFACE PROPERTIES

Consider an element M which has atoms 2 A.U. in diameter and crystallizes in cubes. Then a cubical particle with sides 2  $m\mu$  will have 10 atoms of M in each direction, so will contain 1000 atoms. Of these 512 will lie in the interior ( $8 \times 8 \times 8$  atoms) and the remaining 488 will be on the surface. So a mass of material consisting of particles of this size will have 49 per cent of its atoms on the surface.

Consider next the same element in cubes of sides 10 times as long—20  $m\mu$  or 100 atoms each way. The total number of atoms is now  $100^3$  or 1 million, the number of internal atoms is  $98^3$ , leaving the number of surface atoms at about 60,000. Thus material of this size has 6 per cent of its atoms on the surface.

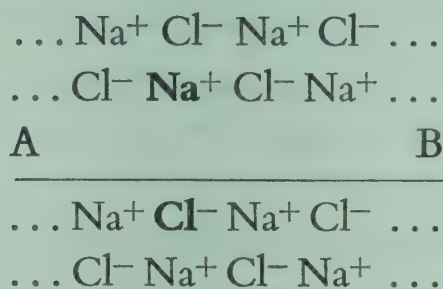
From here on, the relative numerical importance of surface atoms falls to one-tenth with every tenfold multiplication of the side of the cube. By the time we have reached a particle of 20 microns (when the substance will still

<sup>1</sup> The Greek letters  $\mu$  and  $\gamma$  indicate the millionth part of the respective units, metre and gram. The millimicron is better written  $m\mu$  (compare mm. for millimetre); the form  $\mu\mu$ , which is sometimes used, is strictly the millionth of a micron.



be impalpable or “silty” to the touch) surface atoms are down to .006 per cent or 60 per million.

The reason for this emphasis on the number of surface atoms is that they differ markedly from those in the body of the solid. While any atom in the interior is electrically satisfied, one on the surface is still unsatisfied. If we confine ourselves to ionic compounds, which are of chief interest in soils, we can see this point most easily by supposing that a sodium chloride crystal, seen in section in the diagram, is suddenly sliced along the line AB, exposing a new



surface in each fragment. The sodium ion in black type has suddenly been deprived of a neighbouring chloride (also black). It is therefore a positive centre of attraction for negatively charged ions from “outside”, to make up for the affinity which it has lost. At the same time each chloride ion that is freshly exposed is a negative centre of attraction for cations. This effect is general. If we consider minute crystals of an insoluble substance like silver bromide dispersed in water, these will attract ions from the solution to their surfaces as described.

These foreign ions are said to be *adsorbed*. No exact chemical formula can be given to a particle containing adsorbed ions on its surface; there is no “Law of Simple Proportions” in this realm of chemistry.

Many of these foreign adsorbed ions are too firmly attached to be washed out by water. They appear as “impurities” on the precipitates which we prepare in analytical work. Thus a precipitate of  $\text{BaSO}_4$  may easily contain 1 per cent of its weight of impurity<sup>2</sup>, attached in this manner. The same thing happens to bigger crystals, but a coating of impurity one atom thick over the surface of a perfect crystal even as small as 20 microns is trivial. Particles of colloidal size, however, may hold important amounts of foreign atoms on their surface.

In spite of the original existence of both positive and negative centres of attraction on a surface, one kind of attraction normally prevails, so that the surface becomes either a positive or a negative sheet through the adsorption

<sup>2</sup> A precipitate to be easily filtered should not be finer than 5 micron. The argument on the previous page shows that a perfect crystal of this size should contain only 0.02% of surface atoms. The apparent contradiction is explained by the fact that these tiny crystals are built of smaller blocks which are joined together but do not fit perfectly. Thus these 5-micron particles have an interior surface many times greater than the exterior.



of excess ions of one sign or the other. Which it will be depends on the chemistry of the individual substance. The colloids of soil, both organic and inorganic, are negatively charged, as is shown by their migration to the anode on electrolysis; they therefore attract positive ions (cations) electrostatically.

### CATIONIC EXCHANGE

The cations are held firmly on the outside of negative colloids, and only a small proportion, often less than 1 per cent, dissociate into the surrounding solution, so forming an "ionic atmosphere" around the particle. However, they may all be replaced by any other cation that is added to the system. Suppose for the moment that we have obtained our colloidal particle in the solid state, that it has 200 excess negative charges (the true figure is many times as great for soil colloids), and that to balance the charge it has attracted various cations of which 100 are univalent and 50 bivalent. If we wash (or *leach*) such a substance on a filter with an excess of a concentrated ammonium salt—say ammonium acetate—the ammonium ion competes with the original cations for a place on the colloid, and on continued washing it drives them out completely into the solution. Even though ammonium ions are not powerful competitors, their numbers in this action are overwhelming. The extract may be analysed, and the result reveals the relative amounts of the cations originally attached (see Fig. 15

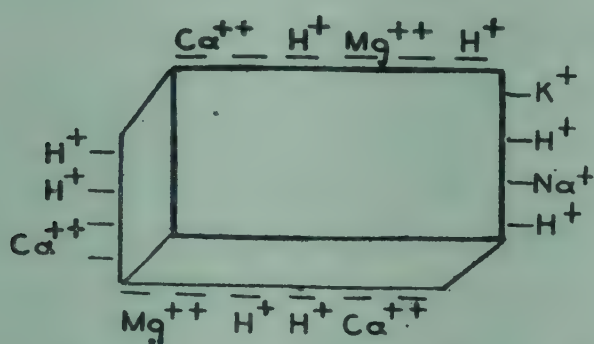
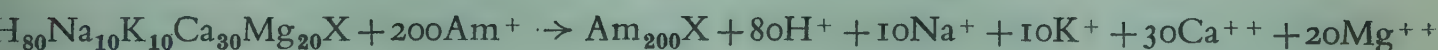


Fig. 15. Adsorbed ions on surface of soil colloid  $\text{Ca}_3\text{Mg}_2\text{NaKH}_8\text{X}$ .

for a simplified version of this). Writing X for the big colloidal negative ion we might get:



(The acetate ions are the same on both sides of the equation and are left out for simplicity.)

Ionic exchange is a general characteristic of colloids, but it has attracted most attention in two fields—namely, water-softening and soils. "Hard" water contains calcium ions which form a precipitate with ordinary soaps. If such water is allowed to filter through a solid which has sodium ions adsorbed on its surface, the calcium replaces the sodium on the solid, and an equivalent amount of sodium passes into solution. The treated water no longer precipitates



soap, and the solid "softener" can be renewed from time to time by washing out the adsorbed calcium with a sodium salt. We commonly use the terms "calcium colloid" or "calcium clay" to describe a colloid or clay in which that ion is predominant among the exchangeable ions.

### ANIONIC EXCHANGE

While most of the familiar colloidal systems consist of negative particles, positive colloids also exist. Everything that has been said of the adsorbed ions on negative colloids applies here also, with the signs changed. Thus anionic exchange takes place on the surface of positive colloids; for example, one might have a competition between chloride and sulphate on the surface of a particle Y with 200 excess positive charges:—



The deep brown colour obtained when ferric chloride is dissolved in water is due to colloidal ferric oxide formed by hydrolysis. This has a positive charge, due to  $(FeO)^+$  groups which in turn hold chloride ions in the adsorbed state on the surface. The formula of such a particle might be  $Fe(OH)_{2.983}Cl_{0.017}$ , where as before there are no simple proportions; the particle also holds a great deal of water, again in no exact proportion.

The inorganic colloids of soil have some capacity to adsorb anions, in spite of their dominant negative charge (see p. 80).

### THE INORGANIC COLLOIDS OF SOILS

Ionic exchange in soils was first noted by Way in 1852, but its nature was not understood until recently. It is shown by both the inorganic and the organic colloids of soil and to a less extent by the fractions of larger dimensions. Since the organic fraction is often very small, the inorganic colloidal fraction is of primary importance. This can be separated from the rest of the soil by means of its capacity to stay dispersed in solution while larger particles settle (see p. 204):

The property of cationic exchange was first discovered in naturally occurring silicates called *zeolites*. For this reason synthetic materials used in water-softening are sometimes called zeolites, and similarly when cationic exchange was discovered in soils it was ascribed to zeolites. We know now, however, that zeolites are not present in soils; it would be better for the word to be limited to its original meaning. The nature of the colloidal particle "X" in soils will be dealt with later; our first concern is with the adsorbed exchangeable cations.

We are interested in these exchangeable ions for several reasons. Their total amounts are important, since exchangeable ions are easily taken up by



plants. Their relative proportions are also important; they determine the pH of the soil and its physical relations to water. This last effect is of immediate concern, and is discussed in the next paragraph.

### STABILITY OF COLLOIDAL SOLUTIONS

Particles of colloidal size are small enough to remain in suspension for long periods—or even indefinitely just like ordinary molecules. Such a suspension is called a *colloidal solution* or *sol*. In contrast with this, a suspension of fine sand or silt—that is, of particles of two microns upwards—settles in water in a few hours. The difference in behaviour of the smaller particles is due to two effects. In the first place, their rate of settling under gravity is very slow because their large surface causes resistance to movement; secondly, they are small enough to have a diffusing motion which may be upwards as well as downwards, just like ordinary ions or molecules, except that being larger than simple molecules they diffuse more slowly. (This effect, called *Brownian movement*, is observed in the ultra-microscope.) Thus, a sphere of quartz of diameter 0.2 micron falls through water at the rate of  $3.5 \times 10^{-6}$  cm./second, or one centimeter in 80 hours, while a sphere of one-tenth this diameter takes 100 times as long—that is, a year—to fall a centimeter (see Stokes's law, p. 203). Meanwhile, however, the gradual process of diffusion carries the particle back to the more dilute upper levels; so if we are dealing with vessels only a few cm. high, a stable distribution is reached by which small particles remain suspended indefinitely. This final distribution, as a compromise between diffusion and gravity, has an exact analogy in the atmosphere. Diffusion without gravity would carry all the gases of the atmosphere into outer space; but under the action of gravity each gas is held by the earth and distributed with its own concentration gradient, becoming more dilute the further it is from sea level. At ordinary levels the composition of the atmosphere is essentially uniform, like a colloidal solution in a beaker. Only when we consider heights above those of the ordinary laboratory does the concentration gradient become important.

However, if several colloid particles coalesce, the aggregate that is formed sinks to the bottom on account of its greater settling velocity. The solution is then said to *flocculate*. If the particles are closely associated with a sheath of water molecules—or, as is usually said, if they are highly hydrated—they have little tendency to coalesce and the solution is stable. Three factors determine the stability of any colloidal system—the total salt concentration, the nature of the adsorbed ions, and the nature of the colloidal particle itself.

(i) The effect of salts can be expressed in the simple principle that the greater the total salt concentration the greater the tendency to flocculate. This effect



is due to a competition between the salt and the colloid for the water of hydration which normally sheathes the colloid. However, added salts are also important in affecting the second factor—the nature of the adsorbed ions.

(ii) The adsorbed ions. Confining ourselves to the negative colloids of the soil, the important cations are Na, K, Ca, Mg and H. We can separate these into two groups. Sodium, and to a lesser extent potassium, colloids, are very stable in solution, and even when flocculated by an excess of salt they are relatively bulky and gelatinous. The solids swell in water and are easily dispersed—that is, sent into colloidal solution. The reason appears to be that the particles have large ionic atmospheres with many cations relatively remote from the centre (Fig. 16A), and such particles do not easily come together<sup>3</sup>.

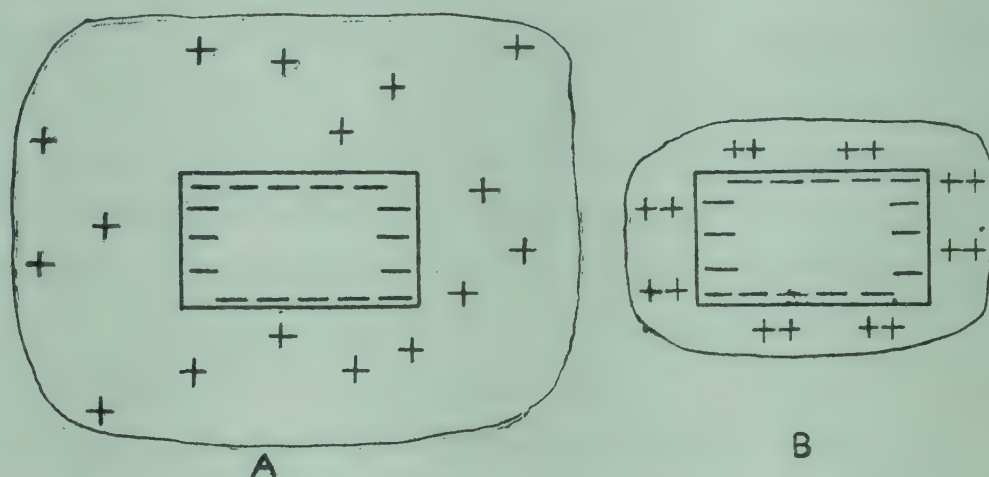


Fig. 16. Ionic atmosphere of negative colloid saturated with sodium (A) and calcium (B). This is highly symbolic and the difference is exaggerated. Simple anions from the surrounding solution may also be present; but the cations are in excess there by 16; the positive "atmosphere" comprises all that region where cations are in excess.

Calcium and magnesium colloids flocculate much more easily and are more compact when flocculated, their ionic atmospheres also being more compact (Fig. 16B) on account of the higher valence of the ion. Colloids holding ions of still higher valence are still more unstable in solution. Acid clay itself—that is, the colloid in which hydrogen ions occupy the positions on the surface—is also easily flocculated, as are the acid forms of other negative colloids. With clay as with other negative colloids, the more alkaline the environment the more stable the solution. The reason is simply that clay is a weak acid, which ionizes less than its alkaline salts. Like many weak organic acids, it is also less soluble than its alkaline salts.

(iii) Colloidal systems themselves, irrespective of salts and adsorbed ions, vary from the most stable to the most easily flocculated. These contrasting types

<sup>3</sup> The theory of flocculation even today is difficult and controversial. The common explanation of the high stability of sodium colloids in terms of hydration of sodium ions will not do, since calcium ions are more highly hydrated. Neither has a satisfactory explanation been given for the difference between sodium and potassium in colloid chemistry.



are called *hydrophilic* and *hydrophobic* (water-loving and water-fearing) respectively. Clay is a typical hydrophobic, or easily flocculated, colloid, as compared with starch and glue which are hydrophilic. Most hydrophilic colloids are just very big water-soluble molecules; starch, like sucrose, has a high proportion of water-attracting groups in its molecule, so is highly hydrated in solution. Some organic colloids of soil are more hydrophilic than clay—for instance, the colour of peat streams is stable. But clay sols also differ widely among themselves from highly hydrophobic to somewhat hydrophilic.

The main practical interest of these comparisons lies in the relative ease with which clay may be dispersed by rain. A clay that passes easily into colloidal solution fills up the pore spaces and so causes poor aeration. A clay that remains flocculated, on the other hand, is an indispensable condition for good aeration. (See, however, p. 82).

#### EXAMPLES IN SOILS

The effect of a *sodium* salt is to disperse the soil colloid. This is due to the stabilizing effect of sodium as an exchangeable ion. The salt as an electrolyte, whether chloride, sulphate or nitrate, works the other way, but the net effect is as stated unless the salinity is intense, and this accounts for the downward movement of colloidal clay which has occurred in Mallee profiles in which NaCl has played a part. This effect is sometimes called *solonizing*.

The effect of a *calcium* salt is to flocculate, both as a salt and as an exchangeable ion. If free  $\text{CaCO}_3$  is present, then normally the  $\text{CO}_2$  of the soil produces a fair concentration of the bicarbonate  $\text{Ca}(\text{HCO}_3)_2$ , enough to cause flocculation. A calcium clay, however, in the absence of bicarbonate, is more easily dispersed by water than is a pure hydrogen clay. The heavy claypans of the red-brown earths bear witness to this fact.

#### *Lime and Gypsum*

Both these compounds are added to heavy land in order to improve the structure. The main effect is to provide calcium ions. Since gypsum has a solubility of 0.2 per cent  $\text{CaSO}_4$  containing 0.06 per cent calcium, it is more effective in saturated solution than lime, which even in an atmosphere of 1 per cent  $\text{CO}_2$ —which is a high concentration for surface soil—can only provide half as much calcium in solution in the form of bicarbonate. Gypsum at the rate of 30 cwt. raised the yield of oats from 34 to 51 cwt. per acre in a wet year at Werribee; the treated land was drier and gave far better germination and early growth than the untreated or the limed plots. Lime, however, often has a better long-range effect on the physical nature of the soil than corresponds simply to calcium ions, (p. 82). Both gypsum and lime introduce calcium into the adsorbed cations, though in different ways; the calcium of gypsum enters



by cationic exchange ( $\text{Ca}^{++} + \text{H}_2\text{X} \rightarrow \text{CaX} + 2\text{H}^+$ ), while the calcium of the alkaline lime enters rather by the neutralization and destruction of exchangeable hydrogen. ( $2\text{OH}^- + \text{H}_2\text{X} \rightarrow 2\text{H}_2\text{O} + \text{X}^{--}$ , leading to  $\text{CaX}$ ).

### *Reversibility*

Hydrophobic colloids are usually not reversible. That is, if they are dried they do not go back into suspension the next time they are wetted, or may take a long time to do so. This is shown by soil colloids after a long spell of hot, dry weather. The soil may not be dispersed when the first rain falls, but will only slowly come back to its more normal state of dispersion after some days or weeks of wetting. This incomplete reversibility is supposed to be a good thing in the Sudan, where heavy clay soils are irrigated and where the intake of water would be very slow if the clay became normally dispersed.

### *Effect of Burning*

The colloids of the soil are permanently changed by heating, and clay is converted either to brick-like fragments or to a fine red dust which no longer disperses in water. English writers mention the practice of deliberately burning clods of heavy soil and subsequently scattering the product over the same land. This can hardly have improved the texture appreciably unless done on a gigantic scale; but it may have had a profound chemical effect, of the nature of which as yet we know little.

### NATURE OF ANIONIC PART OF CLAY

Soil colloids differ greatly not only according to the adsorbed cations but also in the nature of the negative particle itself, denoted as X in the equations for cationic exchange. If we prepare two hydrogen-saturated colloids by decantation, one from the chernozem-like soil of the Wimmera and the other from the red loam (krasnozem) of Gippsland, the former is very much stickier, swells more on wetting, and forms a more stable suspension in water than the latter. The red soils of Gippsland are friable and porous and can be worked soon after rain in spite of their high percentage of colloid; and in this they resemble the krasnozems further north, as at Lismore, N.S.W., and in equatorial climates, as in Java or New Guinea.

These two colloids represent the two main groups that are known in soils (see Table II). On the one hand are the grey colloids (nos. 1, 2, 4), relatively high in silicon and low in aluminium and iron; on the other, the red colloids (nos. 3, 5), relatively low in silicon and high in aluminium and iron (or in the "sesquioxides", as the pair  $\text{Al}_2\text{O}_3$  and  $\text{Fe}_2\text{O}_3$  are often called). All these are "secondary" compounds, being formed in the soil itself and not present in the parent material. Like most colloidal particles, they consist of minute crystals



which give characteristic X-ray photographs, so that the fraction from any soil can be identified by its X-ray spectrum, which shows the characteristic lines of one or more pure clay minerals. These spectral lines correspond to the spacings between groups of similar atoms in the crystals. Information on Australian colloid minerals is scanty. Amorphous material also exists in soil, and gives no X-ray lines; most workers believe that this is unimportant in amount.

TABLE II  
SILICA-SESQUIOXIDE RELATIONS OF CLAY FRACTIONS  
(LESS THAN ONE MICRON)

Soil	Parent rock	Percentage			Molecular Ratio	
		SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	$\frac{\text{SiO}_2}{\text{Al}_2\text{O}_3}$	$\frac{\text{SiO}_2}{\text{R}_2\text{O}_3}$
1. Grey surface, acidic	Wash from Silurian mudstone	48.8	24.6	5.2	3.3	2.9
2. Yellow subsoil, acidic	Do.	42.5	27.0	9.5	2.6	2.2
3. Red loam, surface	Basalt (Oligocene)	35.3	24.3	16.4	2.4	1.7
4. Calcareous clay subsoil	Basalt (Pleistocene)	51.4	22.5	11.4	3.9	2.9
5. Yellow subsoil, acidic	Granite	24.5	28.8	16.8	1.4	1.0

Soils 1, 2, 3 are from survey of Berwick, Vic. (*P. Roy. Soc. Vic.* 52, 234), 1 and 2 being podzolic and 3 a krasnozem. No. 4 is the subsoil of a chernozem-like type, pastoral Western District (*P. Roy. Soc. Vic.* 49, 103). No. 5 is "lateritic" from land with cobalt deficiency, south-western W.A. (*C.S.I.R. Bulletin.* 115).

The grey siliceous colloids are found particularly in the drier climates; their best-known members are called *montmorillonite* and *beidellite*. *Hydrous mica*, or *illite*, with potassium within its crystal, is also widespread. The red sesquioxidic colloids are found in soils that have been severely leached, and comprise *kaolinite*, *halloysite*, and free *aluminium oxide* and *ferric oxide*, both anhydrous and hydrated, the ferric oxide being responsible for the colour. Montmorillonite, beidellite and kaolinite are plate-like, and halloysite is fibrous; the actual particles were first photographed in 1941, using the electron microscope, which records the shape and size of particles down to about 10 millimicrons. Whether plates or fibres, the particles are very thin in at least one dimension. This accounts for the peculiar silky or streaky appearance which soil or clay suspensions have after stirring. The particles follow the line of flow,



with a thin edge pointing forward, so the suspension reflects light to a different extent from different directions.

Taking montmorillonite to represent the siliceous colloids, and kaolinite the sesquioxidic, these differ in two important properties; montmorillonite has a higher capacity for adsorbing cations than kaolinite and forms more stable suspensions. The first difference might be expected from the crude chemical formula<sup>4</sup>; montmorillonite contains four molecules of  $\text{SiO}_2$  to one of  $\text{Al}_2\text{O}_3$ , while kaolinite contains two. The structure of the crystal gives a better explanation. Seen in cross-section, the thin plates of montmorillonite consist of the sequence O-Si-O-Al-O-Si-O; kaolinite plates have O-Si-O-Al-OH. The former has two surfaces (Si-O-) capable of attaching cations, the latter has one. However, a more important difference is that the montmorillonite plate has a negative charge because Al atoms occupy some of the places in the crystal where one would expect Si to be; since the valence of Al is one less than that of Si, the whole crystal now attracts cations from outside, electrostatically. At the same time some Mg atoms occupy some of the regular places of Al, again raising the negative charge. These replacements do not happen in kaolinite. Further, the aluminium in kaolinite is exposed, in montmorillonite it is shielded. Thus the former can adsorb anions, and has not itself the marked anionic property of the latter. We may connect this difference with the greater ability of montmorillonite to form stable suspensions with a negative charge. The swelling of the siliceous colloids with water is another aspect of their relative ease of dispersion in water.

It is interesting to estimate the value of the particle charge  $X$ , though this can only be rough. The size of clay particles depends on the mineral, and varies a good deal within each mineral. Kaolinite is often large ( $1\mu$ ), montmorillonite may be very small ( $10\text{ m}\mu$ ), thus again having a higher adsorbing power per gram. To give some idea of  $X$ , we can consider a particle  $50 \times 50 \times 10\text{ m}\mu$ , a millimicron being  $10^{-7}\text{ cm}$ . If this has a specific gravity of 2.5, it weighs  $50 \times 50 \times 10 \times 10^{-21} \times 2.5\text{ gm}$ , or  $62.5 \times 10^{-18}\text{ gm}$ .

If further this clay holds 0.5 milli-equivalent<sup>5</sup> of exchangeable cation per

<sup>4</sup> The formulae of individual clays are complex and are not useful to quote, since it is the architecture of the crystal and not the formula that matters. Every crystal can fit other atoms into its structure besides those of the ideal formula, on the condition that the "other" atoms must be of very nearly the same size as those they replace. Thus ferric iron replaces aluminium in some clays. Magnesium also can occupy some of the places held by aluminium in montmorillonite (and so incidentally lead to a higher negative charge on the particle). Drastic grinding exposes this non-exchangeable magnesium which then appears on analysis to be exchangeable, which is incorrect. Colloidal hydrous mica on drastic grinding similarly releases non-exchangeable potassium, which is normally held between pairs of silicon-oxygen sheets. The existence of K and Mg in clay anions explains the natural retention of these elements in soils while Ca and Na are removed.

<sup>5</sup> See p. 167.



gram, the particle holds  $62.5 \times 10^{-18} \times 0.5 \times 10^{-3} = 31.2 \times 10^{-21}$  equivalents of cations, or using Avogadro's number  $0.6 \times 10^{24}$ , the particle holds 19,000 cations. This then is the value of X. Further, if we suppose that all the cations are held on the two flat sides, the area on which they rest is 250,000 square Angstrom units (10 A.U. equals 1 millimicron), so that there is one cation to every 12 square Angstroms of surface. This may be compared with the area of about 3 square Angstroms which a sodium or a calcium ion actually occupies. In fact the exchangeable ions are less densely packed than just stated, since the particle is permeated with cracks and channels and so has a larger surface area than has been calculated.

### *The Exchange Properties of other Fractions in the Soil*

1. Organic colloids have two to three times as great a cation-holding capacity as common siliceous colloids weight for weight, and may be responsible for holding most of the cations of a sandy soil. Some of them are more hydrophilic than the inorganic colloids, but they do not make the soil sticky. Some of the organic material is very hydrophobic, and may be important even in very small quantities in forming aggregates that are stable to water.
2. The inorganic fractions above colloidal size also contribute to the total exchange capacity of the soil. The coarser clay fraction ( $0.2-2\mu$ ) is generally so close in behaviour to the fraction below  $0.2\mu$ , which all chemists agree to call truly colloidal, that it makes little difference in practice whether we confine our definition of soil colloid to the smallest particles or extend it to 2 microns as many soil chemists do. The existence of fairly high exchange capacity in some particles above 2 microns is presumably due to their having a large internal surface as well as their normal, visible surface.

### APPLICATION TO PHYSICAL PROPERTIES OF SOIL

The different structures of soils may be expressed partly in terms of their colloid fraction. It is colloid that binds particles together. A pure sand, whether coarse or fine, contains no colloid, and its particles are just individuals with no cohesion; it is said to have "single-grain" structure. However, most soils contain considerable amounts of colloid, and so form some kind of aggregate. If the colloid is easily dispersed in water, and forms a stable suspension, two effects will be noticed. Firstly, there will be few or no water-stable aggregates, but the soil will separate when wet into colloid suspension and non-colloid single grains. Secondly, on account of this dispersion the colloid fills the spaces between the grains so that the soil sets to a massive state on drying. Thus the same soil contains large clods but few water-stable aggregates, so is difficult to handle whether wet or dry. The situation is different if the colloid is flocculated,



that is, in a state in which dispersion by water is very slow or even absent. The particles which the colloid joins together will now form a water-stable aggregate, which has little tendency to unite with other aggregates to set to a hard mass, and does not stay sticky after rain.

One aspect of the swelling of colloids has already been mentioned, namely the massive movement of soil in the "crabhole" types. Another aspect is seen in the weathering of a clod isolated from a heavy horizon on exposure to the atmosphere. The colloid shrinks on drying, and cracks form which cause the clod to shatter. On re-wetting, each fragment swells further than was originally possible, so that the next drying causes still further shattering.

### *Nature of Good Structure*

While we can understand the bad properties of dispersed soils as just stated, we still have much to learn about the nature of good structure. Flocculation alone does not create good structure, though it is a necessary condition for it. Some heavy subsoils which are completely flocculated have a poor structure, with few aggregates greater than .05 mm. We do not know why crumbs so often become stable just in the desirable range between  $\frac{1}{4}$  mm. and 2 mm. It seems, however, that an irreversible organic colloid, presumably a microbial product, plays the main part in forming these larger crumbs. At any rate, good structure is particularly developed in neutral or alkaline surface soils containing ample calcium and not too low in organic matter—preferably rich in organic matter, like the chernozems. We can relate this to the practical experience of farmers, namely, that lime and green manure improve the soil physically. Further, cultivating the same land for many years is known to make it more cloddy and difficult, and this can be attributed to the mechanical breaking of the organic cement, which is not compensated for by fresh synthesis. In all these matters a structure analysis can measure the results of bad management, and it may serve in the future in tracing the course of improvement under pasture or of destruction by cultivation. Krasnozems naturally have a better structure than soils with siliceous colloid, but they too may lose some of their virtue and become powdery after too much cultivation.



## CHAPTER VI

### THE SOIL AS A RESERVOIR OF WATER

IT IS ESSENTIAL FOR HEALTHY GROWTH THAT THE SOIL SHOULD REMAIN MOIST, neither too wet nor too dry. Most of Australia suffers from time to time from too much or too little rain. The whole of southern Australia is commonly dry in summer and early autumn, the drought in Victoria being most intense in the north-west and least in Gippsland and the mountains. Besides this seasonal drought, parts of the Australian wheat belt receive relatively light rain during the cooler months; while most of the well-established districts average from 10 to 13 inches from April to October inclusive, Ouyen is typical of a fair area of Victoria with an average of  $8\frac{1}{2}$  inches. This is not enough to raise a good crop if the soil is bone-dry at the start of the season, so the land is kept under bare fallow for a year to provide more water. The opposite problem, of removing surplus water by drainage, is important in many winters near the southern coast of Australia and sometimes also in north and north-east Victoria, including the wetter wheat-growing areas such as Rutherglen; drainage is also an important part of the management of irrigated land. We have now to see what light our science can throw on these problems. The capacity of the soil to remain moist in dry weather calls first for attention.

#### RETENTION OF WATER

Granular solids can generally retain considerable amounts of liquids when they are first flooded and then allowed to drain. This is due to two facts. Firstly, work must be done to detach a single drop from a body or film of liquid, on account of the attraction which the molecules of the liquid have for one another. Secondly, the solid itself attracts the liquid. The finer particles of soil attract<sup>1</sup> and hold water so firmly that it takes a much stronger force than its mere weight to pull it away. Some of this water is held so tightly that roots cannot use it. The rest can be used by plants, and this portion receives most attention from soil scientists.

#### *Meaning of "Percentage Water (or Moisture) Content"*

When we discuss the relation of soil to water, we have to refer continually to the percentage of water present in a sample of soil. This is measured by drying a sample to constant weight at  $105^{\circ}\text{C}$ . and expressing the loss in weight

<sup>1</sup> These attractions are often discussed in terms of a mythical "surface tension". It is better to avoid this term here, since it was invented only as a mathematical convenience, and it calls up a picture of a tight skin, which does not exist. What is actually measured as "surface tension" is the outside work required to increase the area of the liquid surface by 1 square centimeter—that is, to pull some liquid away.



as a percentage of the "oven-dry" weight. This is a purely conventional point to take, since more water is lost at still higher temperatures; but it is convenient and is universally agreed on. Thus a sample of 10.0 gm. of moist soil loses 2.0 gm. on drying at  $105^{\circ}\text{C}$ . This is recorded as 25 per cent water ( $\frac{2}{8} \times 100$ ) and not as 20 per cent ( $\frac{2}{10} \times 100$ ), since the soil material weighed 8.0 grams. It is also useful to record water as a percentage of the volume of soil. If 10 grams of moist soil occupied 6.7 cc. in the field (apparent specific gravity 1.5) this loss of 2 gm. or 2 cc. equals 30 per cent in terms of volume.

#### FIELD CAPACITY

There is a limit to the amount of water which a permeable, well-drained horizon can hold in the field. This limit is known as the *field capacity*, and is recorded as the percentage of water held in the soil within one or two days after heavy rain or irrigation. This may seem at first too vague for a definition. However, it is a definite and reproducible percentage. After one day the distribution of water in the soil down to the depth of wetting is fairly stable; after two days losses through roots or by evaporation become serious. The effect of applying water to dry soil is to moisten it nearly uniformly to field capacity to a depth depending on the amount of water added. Below this depth the soil changes sharply from moist to dry (Fig. 17). The addition of

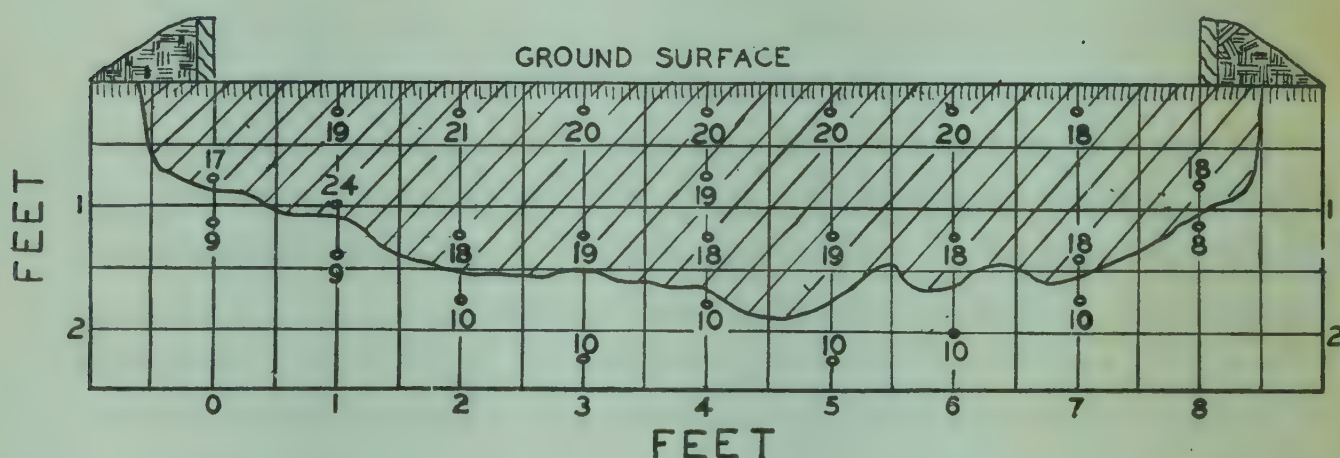


Fig. 17. Percentage of water at various points in section of soil after irrigating, showing moist zone at field capacity (after Veihmeyer and Hendrickson, *Soil Science*, Vol. 32).

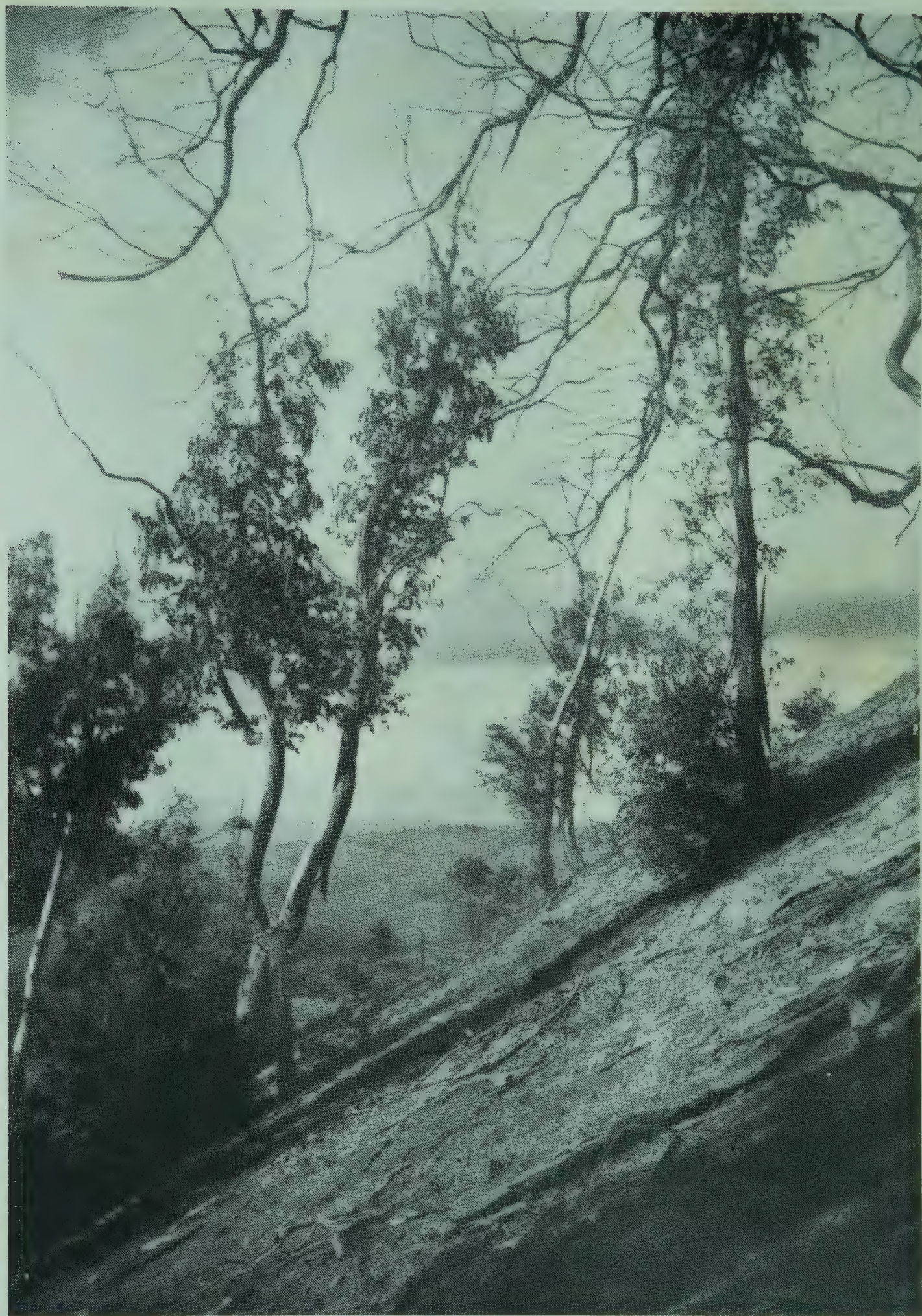
more water does not increase the amount of water held in the upper layers (except for the first few hours) but simply increases the volume of soil that is moistened to field capacity. We can relate this subject to the "penetration profiles" (Fig. 18) of the irrigated districts. It is important for irrigators to know how rapidly each soil type absorbs water. This is found by digging a trench across the furrow carrying the water and noting the position of the line marking off wet from dry soil after three, six, twelve, etc., hours. The soil is at field capacity when the wet front moves only very slowly.





*Plate XI.* Above, salt patch near base of hill, Berwick, Victoria. Sheet erosion has started on the bare soil after vegetation is killed by salt. Below, gully erosion near Broadford, Victoria.





*Plate XII.* Mountain slopes above Omeo, Victoria. Forest floor is overgrazed and burnt and exposed to sheet erosion.



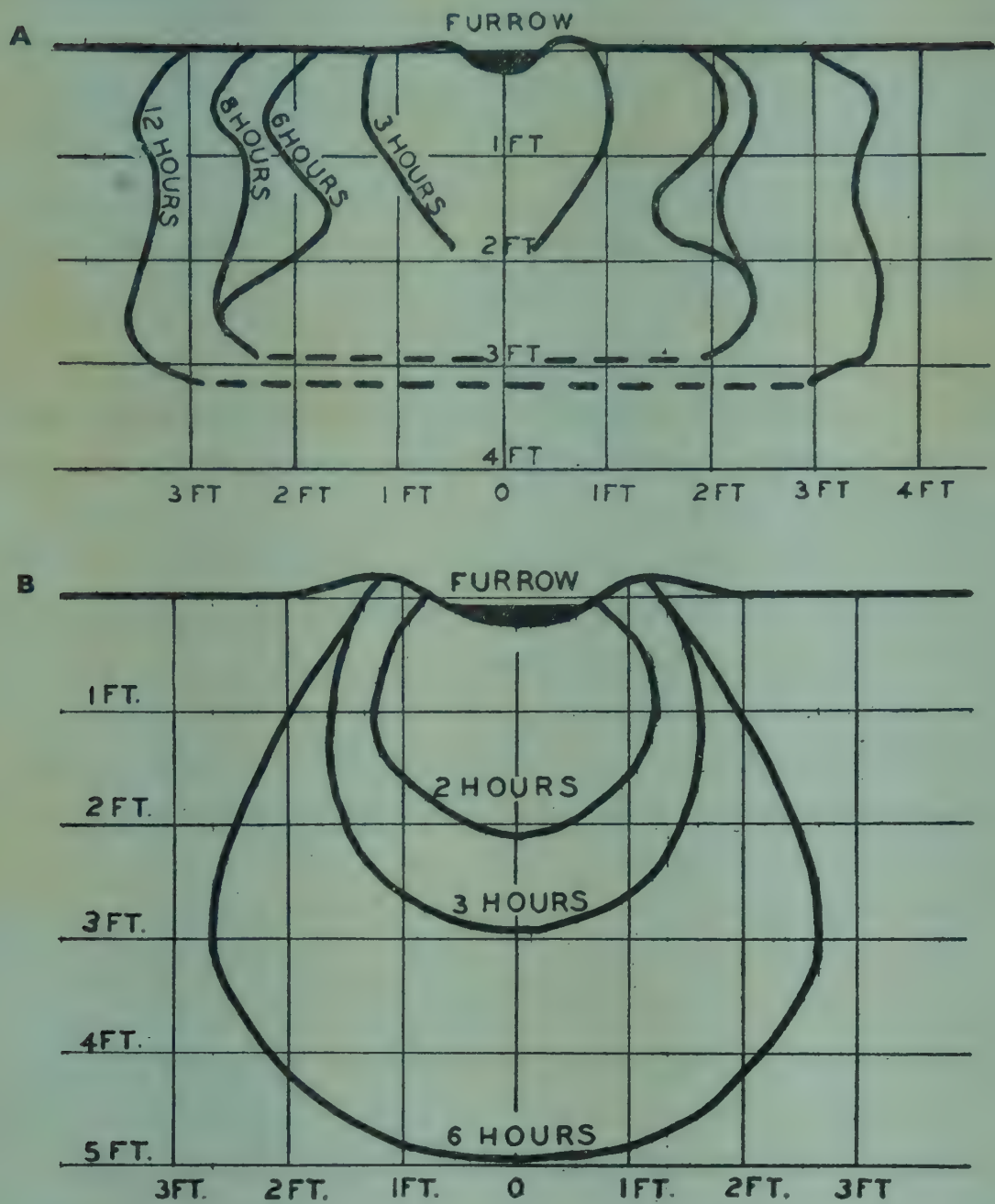


Fig. 18. Penetration profiles, showing position of wet front at different times after adding water. (A) Nookamka loam, impermeable subsoil. (B) Murray sand, uniformly permeable soil. (C.S.I.R. Bulletin No. 149).

Any water in excess of the field capacity is relatively loosely held. Such excessive water is called *gravitational*, because it moves fairly quickly under gravity. If a wet 3-foot column of sand is allowed to drain, the upper levels become free of such surplus water. But this definition needs a word of caution. If a small sample of permeable soil is made thoroughly wet and then allowed to drain on a filter-funnel under gravity, some water will drip through, but the soil will remain much wetter than the field capacity. The surplus water can be removed only by contact with drier soil or some other absorbent material or by some mechanical means such as the use of strong suction. In the field this excess water can move downwards because the layers of soil below can absorb it, in the way just described. This movement is called *capillary* (from the Latin word for hair) in reference to the very fine spaces—fractions of a millimetre—



through which the water has to travel. The process is familiar in the spread of ink through blotting-paper and of water through a towel. The attraction can work upwards or sideways besides the downward direction considered here. The term 'gravitational' is inexact, but is kept here for lack of a better.

The definition of field capacity also insists that the soil must be freely drained. If ground water lies within three feet of the horizon under study (see Chapter VII), field capacity has no meaning.

#### *Approximations to Field Capacity*

There are two laboratory measurements of soil which are sometimes used to give an approximate figure for the field capacity, namely the *moisture equivalent* and the *sticky point*.

The moisture equivalent is the percentage of water which a mass of soil 8 mm. thick can hold against a field of 1,000 times gravity when whirled in a centrifuge for half an hour (not in contact with absorbent material this time). The determination calls for expensive apparatus, and the figure has not the theoretical importance which was once believed. For sandy loams and loams it gives a fair approximation to field capacity, but for sands and heavy soils it has little value, if any.

The sticky point is a crude figure. The worker kneads soil and water to a muddy consistency and then mixes in fresh dry soil until he reaches a mixture which just does not stick to the thumb under a slight pressure. The percentage of water at this stage is recorded as the sticky point. Clearly a soil that is wet enough to stick to the fingers is also too wet for cultivation. An obvious criticism of this figure is that it depends too much on the individual. Further, sands have no sticky point at all. In spite of the drawbacks, it is a rapid method of estimating field capacity and is used in some laboratories in irrigated districts, such as those of the C.S.I.R. at Merbein in Victoria and Griffith in New South Wales.

*Normal moisture capacity* is sometimes used in the same sense as field capacity, but it is better kept to mean the amount of water which the upper part of a vertical column of soil can hold in the *laboratory* after water has been added from above in amount insufficient to moisten the whole column (see appendix). A quick method of estimating this figure—and so of estimating field capacity—is that of Bouyoucos; the soil is first wetted and then drained on a Buchner funnel under a suction of approximately one atmosphere. When no more water comes through, the water remaining in the sample is determined.

#### SIZE OF PORES

Field capacity has an important relation to the size of the spaces between the solid particles. The pore space (which is measured in terms of volume, not



weight) consists of all the space that is occupied by air or water—in other words, all that is not occupied by solid soil particles. The total pore space can be easily determined (p. 101). Commonly it constitutes from 30 to 50 per cent of the volume of a surface soil; some subsoils are much more compact. This pore space comprises channels and cavities of every size and shape, ranging in diameter from less than a tenth of a micron up to the inch-wide cracks that form on heavy land in a dry summer. The smaller the pore, the more tightly it holds water. An arbitrary line is drawn between pores that still hold water and those that are filled with air when the soil has dried to field capacity. The former are called *capillary*, the latter *non-capillary* pores. The largest size of the capillary pores is about ten microns. This limit of the word in soil science differs greatly from that in common usage, namely about one millimetre. On this account, some authorities use the words *micro-pore* and *macro-pore* respectively. These terms are preferable, but have not yet been accepted.

The pores are chaotic in size, shape, and distribution, as might be expected with such a complex material. Narrow pores are seldom long, and may well open into relatively large cavities. So too, non-capillary cavities may persist in the subsoil even during a very wet spell. Such air-pockets can be vitally important.

#### WATER UNAVAILABLE TO PLANTS

Not all the water held at field-capacity is useful to plants. We may consider a soil which has reached its field capacity under free drainage, and is then progressively dried, whether by direct evaporation or by the action of plants (which eventually transpire the water into the atmosphere). As each portion of water is lost, the remaining water is more tightly held; eventually the soil is so dry that the roots of the plant cannot compete with it for water. This ability of the soil to hold water which is unavailable to plants is due to its colloidal matter; water may be so tightly bound by colloids that it resembles the combined water in such a compound as slaked lime which is only decomposed by great heat. There is, in fact, no dividing line between combined water in the usual sense and that which is held by colloidal matter. The stage at which the plant can no longer obtain water is called the *wilting-point*; if the soil remains below this degree of moisture, plants wilt permanently, however humid the atmosphere.

A soil at the wilting-point continues to lose water if exposed to the air, until at length it reaches equilibrium with the water-vapour which is always present in the atmosphere. At this stage the soil is called “air-dry”, and the amount of water which it holds varies with the relative humidity (see Fig. 19). This water is held *hygroscopically*, just as it is on cotton or wool, and earlier workers tried



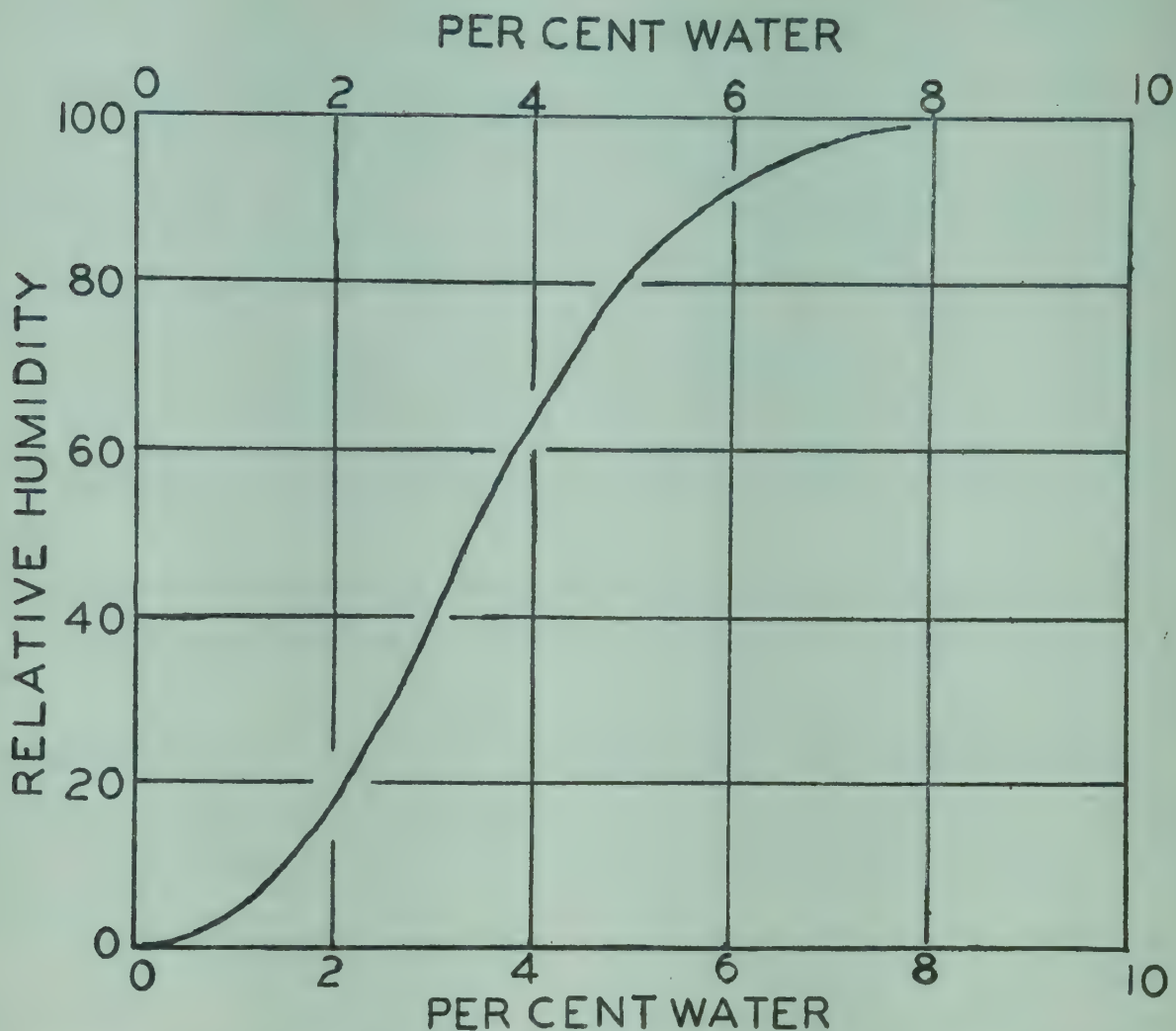


Fig. 19. Hygroscopic water held in Werribee soil (Red-brown earth) as determined by relative humidity.

to work out a “hygroscopic coefficient” by exposing the soil to an atmosphere saturated with water-vapour. However, in a truly saturated atmosphere (which is very difficult to achieve) a soil continues taking up water until it becomes wet; the process is still perceptible after several weeks, though very slow. The hygroscopic coefficient then is fictitious, and in any case it has no practical value. The often-quoted figure in soil analysis, “moisture held in air-dry state”, also conveys little if any information, and might as well be dropped.

The water which air-dry soil holds is driven off on heating. It is conventionally assumed, as already explained, that soil is really dry after it has come to constant weight in an oven at  $105^{\circ}\text{C}$ . In fact the “oven-dry” soil contains water in equilibrium with a relative humidity of a little under one per cent. (The water-vapour in the atmosphere in Melbourne averages about 8 mm., while saturated water-vapour at  $105^{\circ}$  has a pressure of 906 mm.) On further heating, this very tightly-held water is also lost; but as the temperature rises the characteristic properties of the soil are destroyed; the organic matter chars and the clay loses combined water. The fiction that soil heated to  $105^{\circ}$  is quite dry is therefore a useful one. However, even this relatively gentle heat



has a slight permanent effect on the soil; an oven-dried sample should not be used again for physical tests, even though it picks up water from the air apparently normally.

### pF SCALE

The intensity with which water is held by the soil increases so rapidly as the soil dries—in other words, its freedom of movement decreases so rapidly—that in order to plot this intensity against the water remaining in the soil it is necessary to use a geometric or logarithmic scale, which compresses a graph that would otherwise be unmanageable (Fig. 20).

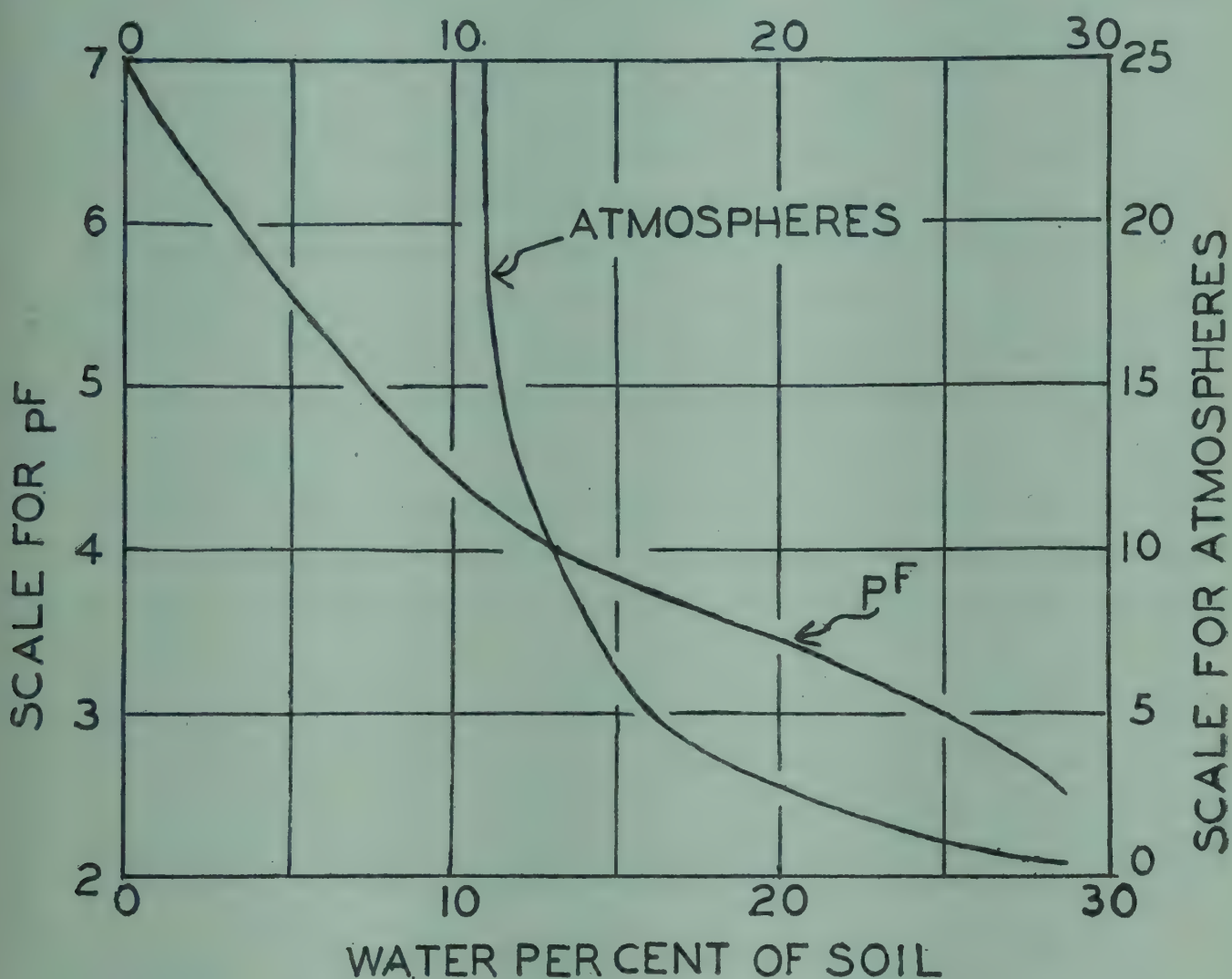


Fig. 20. Relation of water content of soil to intensity with which it is held, with intensity plotted on arithmetic and logarithmic (pF) scales.

The scale that has been widely adopted is called “pF” (p for power to which 10 is raised, F for freedom); this value is the logarithm of the height of a column of water, measured in centimeters, which would exert the same suction as the sample. Thus pF 3 implies that the water is under a tension exerted by a column of 1000 cm. of water—that is, the same height as can be held up by one atmosphere’s pressure. A value of 25 per cent water at pF 3 means, therefore, that the soil retains 25 per cent of water after being drained on a funnel with a



high vacuum on the other side. If we use the formula connecting the height of water in a capillary tube with its diameter,  $dh=0.3 \text{ cm}^2$ , then it appears that a column 1000 cm. high could be held up in a tube 3 microns in diameter. Thus, water held at pF 3 is in pores at most 3 microns wide and so too pF 2 corresponds to 30-micron pores. This scale gives us a method of comparing different soils at different percentages of water but the same true degree of wetness. (Compare Table 12, which shows that a sand with 6 per cent water is effectively as wet as a clay with 34 per cent.)

These curves can be plotted by various physical methods. Nearly all of these refer to results obtained when the soil is becoming drier; the "wetting" curve does not coincide with the "drying" curve, but it is of less interest. Unfortunately these different methods on the drying curve do not always lead to concordant results. One useful determination is that of the freezing-point, which is depressed as the free energy of the water is lowered—that is, as the soil is dried. This method covers the pF range from 2.5 to 4.0, using the formula  $pF=4.1-\log (-T)$  where  $T$  is the freezing-point. But the freezing-point is also depressed by salts in solution, so a sample of moist soil, if at all saline, will give a higher pF value (more tightly-held water) by this method than if one determined directly the tension or pressure required to expel a drop of water from the same soil. It is only in this intermediate range that the discrepancy between the two methods is serious. The points of very high pF are calculated from the relative humidity with which the soil is in equilibrium. Those of pF from 0 to 3 are determined by submitting the wet soil to successively higher tensions. Indirect methods consist of allowing the moist soil to come to equilibrium with some other material (porous pot, or paper) of which the pF curve has already been established. A simple method for the range from pF 1 to 2 is given in the appendix, together with a simple and indirect method for pF 2.5 to 5.0.

The wilting-point lies about pF 4.2; this means a suction of 16 atmospheres (since  $\log 16,000$  equals 4.2). It may be determined directly by growing plants in tumblers in the laboratory and measuring the water present in the soil when they wilt and do not recover in a moist atmosphere; the sunflower is a useful plant for the purpose. This determination is done on the whole mass of soil. However, the water in such a dry sample cannot be evenly distributed (cf. p. 95) and the soil in actual contact with the roots must be drier than the bulk of the soil. On this account one cannot make any exact comparisons between the suction of the soil (16 atmospheres) and that which roots can exert. Several rapid and indirect methods of estimating the wilting-point have been proposed. An old idea was to find the moisture equivalent and divide by 1.84.



Since the ratio of moisture equivalent to wilting-point may lie anywhere between 1.5 and 8.0, this method is only of historical interest. A more recent method relies on determining the pF curve over the range near 4.2, drawing the smoothest line through the points, and reading the value for pF 4.2.

The field capacity does not fit so exactly any pF value. It is often quoted 2.5 to 2.7 but it is a good deal wetter (a lower pF) in some soils. Assuming the value 2.5, the sample of red clay loam from Werribee plotted in Fig. 20 has a field capacity of 27 per cent; since its wilting-point is 11 per cent, after saturation by rain it can hold 16 per cent of water which plants can use. If its apparent density is 1.3, then it holds 21 per cent of useful water by volume, or  $2\frac{1}{2}$  inches of rain in the top foot. In fact this profile has a heavy, impermeable horizon less than a foot from the surface, but the figures illustrate the general principle.

There are two other points of interest in the dry part of the curve. At pF=6.0, the water is in equilibrium with an atmosphere of relative humidity 50 per cent. Since this is a common figure in the daytime during the warmer months, the air-dry state corresponds to pF 6; the sample in Fig. 20 contains about 3 per cent of water when it is air-dry. The value 6.9 corresponds to a relative humidity of 1 per cent, and this is the oven-dry state, so appears as 0 per cent water<sup>2</sup>.

In spite of all these individual points referred to, the pF curve is smooth and continuous. It is convenient for us to distinguish available water from unavailable; but in fact there are all degrees of availability and no clear-cut divisions.

TABLE 12  
FIELD CAPACITY AND WILTING-POINT OF SELECTED SOILS

Soil Type	Wilting-point per cent water	Field Capacity per cent water	Useful water at field capacity
Winkie sand . . . . .	2.4	6.2	3.8
Wakool sandy loam . . . . .	4.3	12.7	8.4
Tulla clay loam . . . . .	10.7	19.8	9.1
Yallakool clay loam . . . . .	14.4	27.4	13.0
Niemur clay . . . . .	16.5	34.3	17.8
Sites clay loam, at 6 feet	57.7	64.7	7.0

The first five are from C.S.I.R. *Bulletin* No. 162 (Wakool).

Sites clay loam is from Oregon Agricultural Experiment Station Bulletin No. 372.

<sup>2</sup> The formulae relating pF to other measurements are given in Baver's *Soil Physics*. The formula connecting pF with relative humidity (R.H.) is:  $pF = 6.5 + \log (2 - \log R.H.)$ . This gives pF=6.80 for a relative humidity of 1 per cent. A soil held at 1 per cent R.H. at 100°C. is drier than at the same R.H. at 20°C., and the higher value of pF=6.9 is computed for this state.



Very few values of wilting-points and field capacities have been published. Five surface soils from the Murray irrigation areas and a deep subsoil from Oregon are quoted in Table 12 and these illustrate the main principles.

The first five types in the table are in increasing order of heaviness. Both wilting-point and field capacity increase with heaviness, and so does the difference between them, which is entered in the last column as "useful water at field capacity". The relative merits of these types depend on the climate. If the rain is heavy enough or persistent enough to increase the water in the soil to field capacity, then the heavier soil (Yallakool or Niemur) holds far more available water than the sand (Winkie), and so supports plants better during a succeeding dry period. However, if rain comes only in light showers of 20 points or so (as is common in southern Australia, e.g. the Mallee), then the soil may not reach field capacity for weeks at a time. A light shower, however, falling on dry land, may raise the sand above wilting-point, and so help a growing crop, while a neighbouring clay still remains below the wilting-point. Further, light rain can penetrate a sand deep enough to escape immediate evaporation, but it cannot penetrate a clay. Thus the sandy soils become more desirable as we move into drier climates. This is well recognized in the desert of the inland; pastoralists value their sandhills because during a drought they grow feed after relatively light rain. The chernozem-like soils characteristic of the Wimmera of Victoria occur in small patches in the adjoining Mallee, but they are not highly valued, being said to be "too good for the climate".

One would expect the amount of "useful water at field capacity" to increase continually with increasing heaviness. However, this does not always happen. Some krasnozems, in spite of their fine texture, have wilting-point and field capacity lying close together. Such soils with high wilting-points must have a high proportion of their pore space made up of very fine pores. It is doubtful whether we can do anything to improve such soils. They are useless for shallow-rooted crops unless the climate is persistently wet. The Sites subsoil of Table 12 has such a high wilting-point that it holds as little available water as a light sand. This is partly, if not wholly, a matter of structure; the roots are *between* the aggregates, in well-drained places, and not *inside* them. A few relatively wide channels are a feature of heavy soils.

This Sites subsoil is not comparable with the others in the Table. Undoubtedly much more water could be forced out of the soil by pressure of 16 atmospheres (pF 4.2) than is indicated by the experimental wilting-point; this statement would not be true of the other soils. However, the values for Sites subsoil are included in order to illustrate an important principle.



## THE MOVEMENT OF WATER IN SOIL

We have now to consider the question, In what way and how quickly does water move in soil? The answer to this is of great importance in a country where seasonal drought is the rule; it is of special interest if we are to understand the practice of bare fallowing, which is universal in the wheat belt of southern Australia.

Water may move in the soil either as vapour or as liquid. We shall consider each in turn.

*(a) Movement as Vapour*

Water vapour moves from places of high to places of low pressure. Now the air in equilibrium with moist soil is practically saturated with water vapour. Even at the wilting-point, the air in contact with the soil is 99 per cent saturated. Thus so long as the soil is wetter than the wilting-point, the only way in which water vapour moves within it is from warm to cool layers, that is, downwards in the afternoon, upwards in the early morning. (This upward movement accounts for the doctrine that dew "rises", as it sometimes does; as everyone knows, dew normally "falls" or condenses from the air). We have no information on the quantity of this movement. However, in warm weather movement of vapour from the surface to the atmosphere is greater than any internal movement can be, as is seen from a simple calculation. Suppose the soil has a temperature of  $85^{\circ}\text{F}$ . at a depth of three inches and  $75^{\circ}$  at six inches, and is at least as moist as the wilting-point. The respective vapour pressures are 1.20 and 0.87 inch while that in the atmosphere is no more than 0.40 inch. The gradient from the 3-inch layer is much greater upwards into the atmosphere than downwards, so the top soil loses its moisture to the air and eventually dries below the wilting-point during the summer day by evaporation alone; in the end its vapour pressure falls to that of the atmosphere. In the above example, if the soil at three inches were at  $85^{\circ}\text{F}$ . and not moist but air-dry, the relative humidity of the soil-air would be  $0.40/1.20$  or 33 per cent; the soil of Fig. 19 would hold 2.9 per cent of "hygroscopic" water. The lower layers, if still moist, now have a higher vapour pressure than the dry surface, so lose vapour to the surface in spite of their lower temperature. Thus the tendency during the summer day is for the soil to dry to a depth of several inches.

During the night and early morning the surface soil cools off and therefore takes up water from the air, even though no dew may form. Thus if the 3-inch temperature fell to  $65^{\circ}\text{F}$ . (at which temperature saturated water vapour has a pressure of 0.62 inch) the relative humidity of the soil air would be  $.40/.62$  or 65 per cent, and the soil would now take up water to a limit of 4.1 per cent on account of its hygroscopic nature. So the loss of water is not cumulative, but



starts afresh each day; further, some of the vapour lost from the surface soil passes to the deeper, cooler layers. For these reasons bare soil does not dry to a great depth in summer. All the same, any device which keeps the temperature down, such as a layer of non-conducting straw on the surface, saves some water.

Movement of water-vapour in the soil has been given little notice by scientists. It may be that during the winter months appreciable amounts of water-vapour move upwards from deep layers to the 1-foot level; at present we can only guess so.

### (b) *Movement as Liquid*

The only time when water moves rapidly through the soil is when it moves downwards during rain, or downwards and sideways after irrigation. Even then the water will not move rapidly, at the rate of several inches in a day, unless the soil contains channels at least  $1/20$ th mm. wide, such as exist in sand or may form in heavier soil as cracks developed during shrinking or left by decayed roots. In the heavier soil, after a few hours of rain most of the channels close on account of the swelling, and movement thereafter is relatively slow.

However, we have seen that water can move through a soil by capillary attraction, independently of gravity. The movement is from regions where the water is less firmly held to where it is more firmly held—from low pF to high pF, from wide to narrow passages. The tendency is thus to equalize the energy. The rate of this movement varies very much with the circumstances.

(i) *Movement from Wet Soil.* When water is poured onto soil, the wetted area quickly spreads not only downwards but also sideways, in the style of ink in blotting-paper. This effect can be seen in a spectacular way in the penetration profile (Fig. 18).

Movement is quick if the soil supplying the water is actually *wet*—that is, wetter than the field capacity or the sticky point. It is another matter if the soil is *moist*—drier than the field capacity, though still containing ample supplies of water for plants. People have been misled by the analogy of the blotting-paper into supposing that water moves with reasonable speed from moist to dry soil also. This does not follow, as will be seen.

(ii) *Movement from Moist Soil.* If we confine ourselves to the normal range between field capacity and dryness, the movement from moist to dry soil seems to be so slow that for most practical purposes it may be ignored.

This statement is in flat contradiction to most traditional teaching. However, it is amply supported by experiment, while the experiments cited on the other side are irrelevant since they start with wet soil. The common laboratory demonstration of the rise of water through glass tubes packed with soil, as followed by the appearance of a moist front, is fallacious in two ways—firstly,



it measures the rise from a trough of water, not from moist soil; secondly, the structure of the soil has been destroyed by grinding. If a tube of soil is allowed to take up water from below and is then lifted out of the water, the moist front hardly moves any further upward.

The modern view is associated with a Californian worker, Veihmeyer, whose experiments were so simple that it is extraordinary that no one had thought of doing them before.

(i) He kept large tubs of soil which were buried so that their surface was at ground level and which could be weighed from time to time. When the tubs were kept bare of plants and exposed to the sun and protected from rain, he found that the soil 8 inches below the surface remained moist after two summers. The soil at this depth does not become hot during the summer (cf. p. 116).

(ii) The trench which shows the penetration of water also shows (Fig. 17) a sharp boundary between soil that is moist to the field capacity and underlying soil that is dry. The existence of this boundary two days after irrigation shows that movement from soil at the field capacity is slow.

(iii) Veihmeyer also kept columns of moist soil in contact with columns of dry soil in tubes in the laboratory. After 138 days only a trace of additional moisture was found in the dry part beyond six inches from the junction.

We can realize from this that if the soil is dry we must give water directly to the root, and cannot expect the water to move towards the root from neighbouring moist soil. Plants suffer from drought when moist soil is a foot away. Veihmeyer's work was done in irrigated orchards, where the constant problem is when to irrigate and how many inches of water to add. Using his results, orchardists have saved a great deal of water by wetting the soil only to field capacity to the depth of the roots. The best interval between irrigations is not found so easily. Veihmeyer, working with prunes, concluded that water was equally available at the wilting-point and at field capacity, and that irrigation was therefore not needed until the soil had dried to the wilting-point. This is a simple recipe, but it is not always correct. Work in Oregon has shown that pears should be irrigated when the soil has dried no more than half-way from field capacity to wilting-point.

Another curious consequence of this slowness of capillary movement is that a pot of soil in which plants are grown cannot be kept at any desired percentage of water throughout its mass. If, for example, one tries to keep the water content half way between wilting-point and field capacity, then if the soil has been dried to the wilting-point and the required amount of fresh water is added, it will simply moisten the upper half of the pot to field capacity and leave the lower half still at the wilting-point. The additional water will be transpired by the plant before it can move appreciably into the dry soil.



*Bare Fallowing for Wheat*

Soil that has been kept under clean cultivation for the previous season holds more water in the top three feet at sowing time than if it has just been ploughed from grassland or from the stubble of the previous year's crop. The difference may reach the equivalent of three inches of rain, which is of great importance where the seasonal fall is less than ten inches; this is largely responsible for the difference in yield of fallow plots and "stubble" plots<sup>3</sup>. Two explanations have been given for this effect. The old view is that cultivation prevents the capillary rise of water from the subsoil to the surface by breaking the capillary channels which carry the water. Once at the surface, the water evaporates and is lost. The modern view is that cultivation prevents the growth of weeds, which otherwise would penetrate the subsoil, absorb water there and lose it to the atmosphere by transpiration. According to the old view it is necessary to work the land after every fall of rain in order to break the capillary tubes. According to the modern view it is not even necessary to cultivate to save water, so long as weeds can be killed in some other way. Cultivation appears from this point of view to be merely a convenient way of killing weeds. It is easy to choose between these rival explanations. If a plot kept bare by hand-weeding retains as much water in the top three feet and gives as good a crop as one kept under clean cultivation, the first explanation is wrong and the second is right. This experiment has been done by officers of the Victorian Department of Agriculture at Longerenong in the Wimmera and at Rutherglen in the North-east of Victoria and gives full support for the modern view. In such experiments it is of course necessary to give the hand-weeded plot enough working to produce a fine tilth for sowing.

One of Veihmeyer's experiments also fits in with this work. In the course of exposing tubs of bare soil, he tried stirring the soil to various depths and found that there was no significant difference between the unstirred and any other tubs in water content after two years. He also showed that a tub lost twice as much water in three weeks through the growth of a single plant as it did in two years through exposure to the sun.

There are other aspects to this problem. Heavy soils crack deeply and so evaporate water from the subsoil; cultivation can cover these cracks. With some soil types, a loose, rough surface obtained by fallowing reduces the amount of run-off of rain down the slope. Fallowing also affects the nitrate content of the soil (see p. 148) but it has not been shown to have any other effects.

With the decline of the capillary doctrines, new methods of preparing the

<sup>3</sup> As an example of the extra water stored in fallow, Penman working at Longerenong Agricultural College in the Wimmera in 1933 found an average of 35.5 per cent water over the top 3 feet on the fallow plot, and 29.2 per cent on the stubble.



land in dry climates have arisen. In Canada, a rod weeder is used which cuts the roots of weeds without turning the soil over, thus achieving the benefits of the fallow without exposing the soil to the risk of erosion by wind. In the Mallee, workers at the research station at Walpeup have tried the "sheeped fallow"—that is, the land is prepared for the following crop by stocking heavily with sheep in the previous season, thus again preventing the loss of water by transpiration without exposing a loose surface to the wind.

It is a curious piece of history. Ingenious people during the last 70 years have persuaded farmers that they were really cultivating in order to break capillary tubes. To-day scientists have abandoned this idea, but farmers meanwhile have become convinced by our predecessors that the difficult theory of capillary movement is true.

#### ESTIMATING WATER RESERVES IN THE FIELD

In managing an irrigated property one should know how much water is retained within reach of the roots at any time, in order to irrigate as soon as more water is needed.

We can always measure the amount of water held in each layer of the profile by removing a sample from each depth and determining the loss in weight after drying in an oven. Steel sampling tubes, which can be forced into the soil to several feet, have been developed for this purpose. However, this is a slow and laborious method.

During the period from 1935 onwards, rapid methods have been invented for estimating the amount of water retained at any depth. Since the use of these is likely to spread, they deserve a description here.

(i) *Porous-pot Manometers or Tensiometers.* A porous pot is buried in the soil at any desired depth. It is filled with water and connected by a tube, holding a continuous column of water, to an apparatus above ground, which records the tension under which the water is held. The soil and the pot compete for the water; as the roots withdraw water from the soil, the tension of the water in the pot becomes greater. The apparatus is obviously limited to tensions below an atmosphere, and in practice can work to about three-quarters of an atmosphere (pF 2.8). Thus this method is only good in fairly wet soil. It may be practically useful all the same. By the time a deep layer begins to be exhausted, upper layers are probably already dry and in need of the next irrigation. Thus the apparatus buried at 3 feet may give valuable information.

(ii) *Gypsum Blocks.* A block is made of compressed gypsum with two metal terminals set inside it an inch apart. The metallic terminals are connected with wire to points above ground and the block is buried at any desired depth. The wetter the soil, the wetter the gypsum block and the higher its electrical



conductivity. Thus using a calibrated scale, by measuring the resistance between the terminals above ground one can estimate the reserve of water in the subsoil, and so decide to irrigate when the resistance has reached a limiting value<sup>4</sup>.

Both these methods are convenient since they only need a reading above ground; however, they both are liable to give false figures if the soil has been disturbed above the pot or the block in the first place. The safest method seems to be to dig a trench and place the pot or block in position at arm's length at the end of a horizontal tunnel, later filling everything in.

<sup>4</sup>An automatic device has been developed whereby sprinklers begin to operate as soon as the resistance of the block has reached a predetermined value.



## CHAPTER VII

### EXCESSIVE WATER: AERATION AND DRAINAGE

TOO MUCH WATER IN THE SOIL MAY DO AS MUCH DAMAGE TO A PLANT AS TOO little water. The amount of pore space between the solid particles is limited; the more water is present, the less space is available for air. Normally the carbon dioxide which is continually produced by roots and micro-organisms diffuses away, and oxygen diffuses in, fast enough to avoid any damage to the plants<sup>1</sup>. If the free air space is small, this diffusion slows up, roughly in proportion to the free space, which probably should not fall much below 10 per cent of the total volume of the soil. Carbon dioxide is always at least ten times as concentrated in the soil air as in the atmosphere (where the normal figure is .03 per cent), and is often recorded as exceeding 1 per cent. In wet and compact horizons, where the total air is small, carbon dioxide exceeds 5 per cent of the air and oxygen itself may be deficient, being eventually all used up by bacteria and roots. In such a waterlogged soil toxic compounds may be formed by bacteria. Plants differ in their tolerance of carbon dioxide—a few are sensitive to 1 per cent—and in their need for oxygen. Potatoes require excellent aeration while many grasses (e.g. Yorkshire fog) tolerate poor aeration. Among the trees of irrigated areas, oranges are particularly sensitive to wetness. Lemons are less sensitive, and pear-trees are very tolerant and are commonly planted in the naturally wet low-lying patches in Goulburn Valley orchards.

When excess water is present, some of the profile may be actually flooded, in which case free water will be seen on digging a hole. This is not always so, however, and we may first deal with aeration in soils without free water.

#### NON-CAPILLARY PORE SPACE

The vital point is how much of the total pore space is still occupied by air when the soil is wetted to field capacity. Soils which contain plenty of such non-capillary pore space are well aerated even in very wet spells; some soils retain some cavities even when they are flooded. Other soils, however, have nearly all their pore space of "capillary" size and these are bad in wet weather. Many fine sandy loams have poor single-grain structure and belong to this class (see p. 81). Heavy soils are not necessarily bad in this respect, since they may be aggregated into large structural units.

For want of any Australian studies of the pore space of a full profile, the following illustration is taken from Oregon. The climate is of the Mediterranean

<sup>1</sup> Simple diffusion accounts for almost all this exchange. Changes of pressure and temperature have little effect.



type, with 40 inches falling mostly in the winter and almost complete drought for four months in the summer. Walnut trees growing on some soil types are seriously affected by the summer drought; on other types they make good growth.

The two extremes of growth are found on a heavy soil, Sites clay loam, and a lighter soil, Newberg silt loam, the trees on the latter being twice as big as on the former. The field capacity and wilting-point were measured for each type at successive 1-foot depths. The difference between these two values, that is the usable water which could be stored at field capacity, averaged 13.6 per cent for the top six feet for Sites and 13.9 per cent for Newberg. In spite of the closeness of these figures, over a quarter of the Sites supply was unused at the end of the season, as compared with one-eighth of the Newberg supply. The reason for this different uptake is shown in Table 13. Sites clay loam is a mature

TABLE 13  
AERATION AT FIELD CAPACITY,  
AND PROPORTION OF TOTAL WALNUT ROOTS, ON TWO SOIL TYPES

Soil Type		Depth in feet					
		0-1	1-2	2-3	3-4	4-5	5-6
Newberg silt loam (good growth)	% air at field capacity	15.6	17.9	24.7	25.7	27.4	34.2
	% roots <i>below</i> this level	—	—	—	64	47	42
Sites clay loam (poor growth)	% air at field capacity	12.0	14.0	8.0	5.0	0.0	2.0
	% roots <i>below</i> this level	—	—	—	10	5	4

(From Oregon Agricultural Experiment Station, *Bulletin* No. 372.)

soil with a heavy B horizon, and its pore space below the top three feet is mostly capillary; thus the aeration at field capacity is low, consequently roots cannot penetrate the lower layers, which are wet during the winter when roots are growing, so the plant cannot use the store of water in the summer<sup>2</sup>. Newberg silt loam, however, contains ample non-capillary space throughout the top six feet. This good aeration extends down to the tenth foot, where roots are

<sup>2</sup> This seems to have happened to apple trees growing on podzols with heavy subsoil to the east of Melbourne.



still present in good numbers. This study shows the value of knowing the nature of the deep subsoil where trees are concerned.

One of the chief virtues of this work on the walnut trees is its simplicity. A chunk of soil is taken from each depth in spring, when it is wet to its field capacity; it is weighed, and its volume is measured by finding how much oil it can displace. This volume is made up of soil material, water, and air. The volume of the water is found by drying a sample and determining the loss of weight. The volume of the soil material is the weight of the dry soil divided by its specific gravity, which is found on a separate sample (it is not far from 2.6 as a rule). The volume of the air is what remains.

This division of the total pore space into large and small is expressed also by the lower part of the pF curve. Pores which are emptied at pF 2 are all greater than  $30\mu$  in diameter; those which are emptied at pF 1.6 are all greater than  $75\mu$  (the relation being logarithmic), and so on. Unless there is a water-table near the surface, all pores as large as this ( $75\mu$ ) are full of air even in wet weather. Some workers have found that the growth of crops in a wet climate is particularly well correlated with the amount of water that can be held between pF 1.0 and 1.6. The rate of infiltration naturally depends on these larger pores; one formula which seems to work fairly well is that infiltration varies with the percentage of the soil volume that is drained between pF 0 and 1.0, plus a quarter of that drained between pF 1.0 and 1.6. Fig. 21 shows two contrasted structures, both soils having the same total pore space (pF 0). Their relative merit depends on the climate. The poor aeration of soil A would not matter in a dry climate, and the good aeration of soil B would compensate for its low water-storing capacity in a wet climate. Fig. 22 illustrates in a different way the contrast between these soils at field capacity (pF 2.5), where as a general rule, non-capillary and capillary pore space should be equal. This further information on structure is complementary to the determination of the water-stable aggregates above  $\frac{1}{4}$  mm. (p. 68). Without a good proportion of such aggregates, non-capillary pores can hardly exist. However, the aggregates themselves may be arranged either like bricks fitting in a wall or like bricks in a pile of rubble; in the former case non-capillary space is low, in the latter it is high.

Thus poor aeration is due to a poor structure and the ideal in ploughing should be to loosen a good structure already formed. There is still a good deal of misunderstanding on this point. It is often taught that one virtue of ploughing is to "let the air in"—sometimes one even reads it is to "let the light in"! Those who say this do not realize that, provided a soil is not too wet, it is automatically aerated by simple diffusion since the pore space is commonly as high



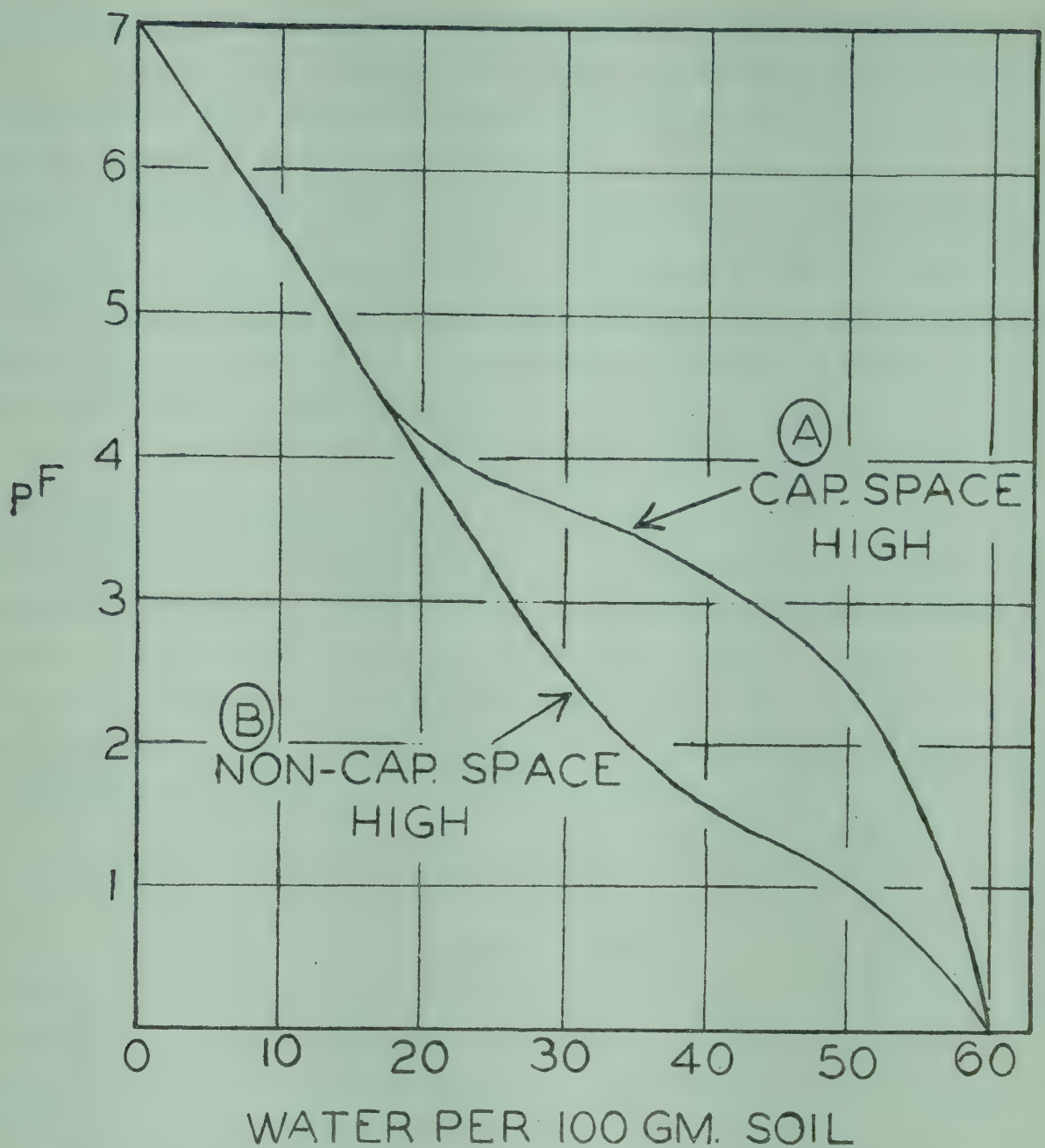


Fig. 21. pF curves of soils of equal total pore-space, with high capillary space in A and high non-capillary space in B. (The zero of the pF scale is here put at  $pF=0$ . This corresponds to a tension of 1 cm. of water. The amount of water held in a soil which has free water 1 cm. from the surface is practically equal to the amount held when completely flooded. In fact the pF of free water flooding the surface is  $\log 0$  or  $-\infty$ , but we can ignore this technical point for the sake of convenience in making the graph.)

as 40 per cent. The pores are certainly very small from our point of view, but they are enormous relative to the molecules of oxygen and carbon dioxide which move in and out<sup>3</sup>.

Thus breaking the surface even of a hard dry soil, while it leaves lumps which check the flow of rain and allow its absorption, and while it provides paths for tender roots, may not affect aeration at all, though it would be rash to say that it *never* improves aeration. In particular, it may prevent the next rain from sealing up the surface altogether. Appearances, however, are deceptive.

<sup>3</sup> The two authorities, Baver (in his book *Soil Physics*) and Keen (in *The Physical Properties of the Soil*) have opposing views on this subject. Keen gives the above argument; Baver does not refer to Keen's argument, but evidently rejects it.



## DISTRIBUTION OF SOLID, WATER, AIR, AT FIELD CAPACITY

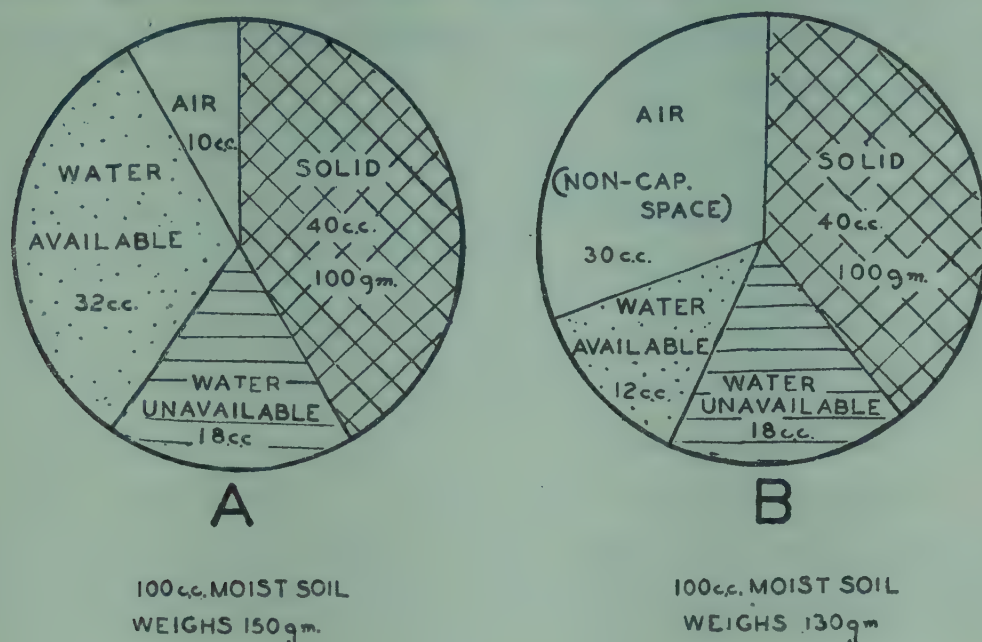


Fig. 22. Distribution of total volume in two soils at field capacity.

A soil that has been under pasture for several years normally has more pore space—and is therefore better aerated—in its original state than after it has been brought under cultivation. Immediately after ploughing, of course, the soil is very loose, and so is temporarily very well aerated. Further, the temporary structure created by ploughing or any later working may allow rain to run rapidly through the ploughed layer. If a compact subsoil is broken up with a subsoil plough, that is another matter; the non-capillary channels thereby formed may remain as part of the structure for many years.

The success of trees in an orchard kept under permanent grass provides further evidence of naturally good aeration. The healthiest of the long-established orange trees on the experimental irrigated plots at Griffith are those under which lucerne has been growing since the experiments started.

It was once taught that pastures should be regularly harrowed to let the air in. We now recognize that the main function of the pasture-harrow is to spread the animal droppings. However, a pasture may be improved by cultivation, not because of any greater aeration but because this may destroy weeds and give other seeds an opportunity to germinate.

Discussions of this kind are common in soil science. There is a vast amount of agricultural lore, as contrasted to our meagre science. An operation on the soil may be valuable for some agricultural reason—producing a seed-bed or killing weeds or checking run-off—and not because of the reasons often given. Many vegetable growers insist that constant cultivation is necessary for getting the best results. This is said where rain is ample, and the reason is alleged to be aeration; but it is difficult to see how aeration can be responsible. Remarkably



few scientific experiments have been carried out on cultivation. The most careful series, done at Rothamsted in England, have shown that intensive hoeing, as compared with hand-weeding, has sometimes reduced yields of sugar-beet, through cutting the roots.

#### WATER-TABLES AND DRAINAGE

Permanent water, often more or less saline, is usually found if one bores deep enough. The depth varies greatly, but in many districts in Australia it is between 50 and 80 feet; that is, if a bore is made to that depth, water enters the bore from the surrounding strata. If the level of this water, the "water-table" as it is called, is lower than about ten feet from the surface, it may be useful for stock or domestic supply but does not directly affect ordinary crops. However, if the water-table stands closer to the surface it may be directly important. Whatever the depth, the soil is fairly wet within two to three feet above the water-table, on account of the upward movement of water by capillarity. This region is known as the *capillary fringe*, and the pF of the water here is from 1 to 2. If the water-table is not too close to the surface it may help the plant by providing some of its water supply from the capillary fringe. On the other hand, if it is too close it restricts roots to a small volume of soil and may bring dangerous amounts of salt (p. 172). We have here a special case of the problem of aeration, namely where free water is present. An English figure for an upper limit for free water is three feet for cropped land and two feet for pasture; if such a level persists as long as a week it is harmful to all but a few special plants such as rice.

High water-tables may form both in wet climates and on irrigated land. Where rainfall exceeds evaporation, as in England and the cooler parts of Europe, the water-table is normally fairly close to the surface. Under irrigation, a water-table is eventually formed within ten feet of the surface, often just above a clay horizon. This is often called a "perched" water-table, since it is commonly not connected continuously with the pre-irrigation water-table which lies at much greater depth. At times excess water may be due to heavy rain following a late summer irrigation, as happened at Griffith in 1931 and at Shepparton in 1931 and 1939, when many fruit trees were killed.

#### *Movement of Water-table*

The level of the water-table has been followed in many countries. It is measured at any point by boring a three-inch hole, protecting its sides with a perforated metal tube and recording the depth to the water at equilibrium. The level is the result of several factors. The water at any point tends to fall towards the nearest outlet, but simultaneously the pressure of subsoil water from higher levels may raise it. Water moves fairly fast or transmits its pressure



effectively through a sandy horizon, and is held up by a heavy horizon. In fact no water-table can form in an impermeable clay horizon. Besides these general movements, plants may lower the level by transpiration. Further, the level is very sensitive to small effects. This is not really surprising since the soil in the capillary fringe is only slightly less wet than at the water-table itself; thus part of an irrigation or fall of rain passing downwards through the wider cracks in the subsoil may raise the level by a foot or more. The level also rises in warm weather and with low atmospheric pressure; this fact unfortunately spoils any attempt to find a steady relation between rainfall and the amount of drainage water.

### *Drainage*

Excess water can be removed by providing drainage channels down which it can flow rapidly. Where the upper horizons are permeable tile drains are buried at a depth of three or more feet; when the water-table rises up to the level of the drain, the water enters between the tiles and runs away rapidly. Where a heavy horizon lies at or near the surface, it is surface water that must be removed. This can be done by digging open furrows or ditches. In some countries with a wet climate mole drains are made by dragging a pointed cylinder through the heavy subsoil at 18 to 24 inches when it is moist. The water flows down the slit left by the blade of the machine and so runs away; the channel is too deep to be either cracked by drying or disturbed by machinery, and it should last five years or more. The mole drain is useful for naturally wet land, the tile drain both for wet climates and for irrigated land.

There is little doubt that large areas near the south and east coasts of Australia would be much improved by drainage. The periodical wetness above the heavy podzolic subsoils during the cooler months not only restricts the range of roots but also delays growth in spring since the evaporation of the excess water keeps the soil cool. While there are many schemes in these wetter parts for removing surface water or preventing water from reaching low-lying ground, the only properties where the subsoil has been drained are those worked intensively for fruit or vegetables. The main interest in drainage in Australia has been in the irrigated areas, where great damage has been done by excess water, notably to oranges along the Murray and in the Murrumbidgee area, and to peaches in the Goulburn Valley. In some of these districts, excess water and excess salt occur together (see p. 172).

In draining a soil one has to decide how deep and how far apart the drains are to be, and their relation to the slope. The accepted view is that drains should run across the line of greatest slope in order to intercept the upper water, but this is not universally done. In particular, where a vineyard has already been



planted, any later drains are normally set along the rows. Depth and distance go together. The deeper the drain the more rapidly will water flow towards it through the subsoil, and therefore the wider its lateral influence. This relation only works, however, in a permeable soil, and in any case anything more than six feet is usually too expensive. Many attempts have been made to work out general formulae for the best depth and distance of drains in relation to soil texture. However, they have not had great success. In the first place, structure is a much better index of permeability than texture is. Some European workers recognizing this fact devised methods of mechanical analysis in which the soil was only gently dispersed; in fact, these are structure analyses in which stable aggregates the size of sand are recorded as sand particles, which is correct for measuring permeability. But even with this improvement, the picture commonly given for the effect of a drain (Fig. 23A), which is derived from a

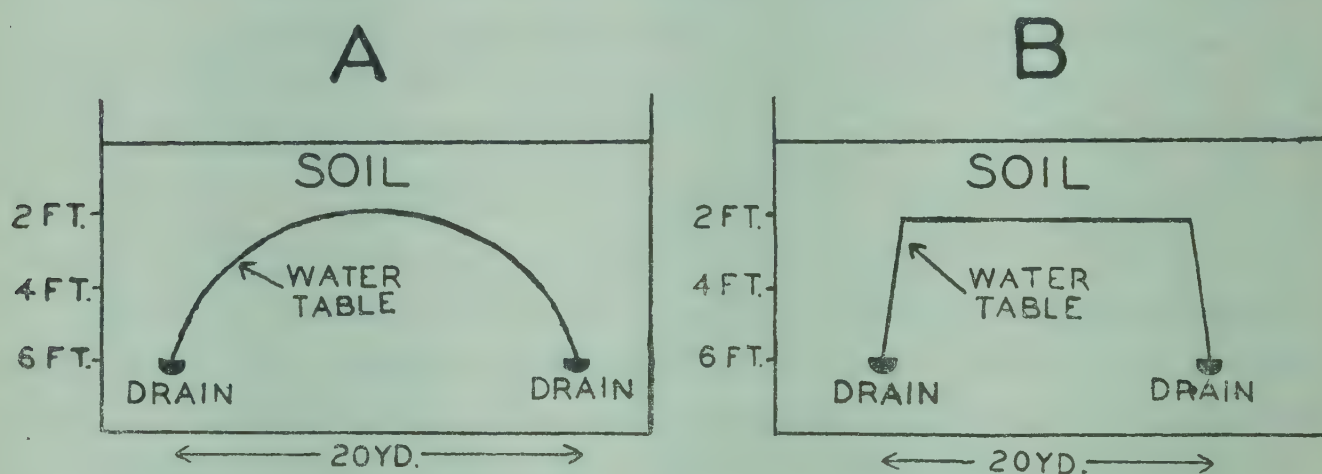


Fig. 23. Position of standing water in soil in relation to drains. (A) Sandy soil (B) Heavy soil.

mathematical formula, is too simple and holds only in exceptional soils which are uniformly permeable. In less permeable soils the main movement of water is along the top of a heavy horizon, and the level between drains is more like Fig. 23B—the water only enters from above the drain, not from all round. The heaviest soils do not form water-tables, but excess water lies on top and may be removed in surface channels or moles.

Eventually workers in the Murray irrigation areas have arrived at a figure for depth and distance of drains for each soil type (Table 14). The tile is usually laid on a horizon which is at least as heavy as sandy clay; nothing is gained by going deeper than the point in the profile at which light clay appears. Such rules of course may be modified if any horizon is aggregated into a good structure; but these Mallee soils do not differ greatly in structure among themselves.

#### *Other Methods of Control Under Irrigation*

Obviously if a water-table is high and no abnormal rain has fallen, the landholder, or perhaps a neighbour must have applied too much water. The



TABLE 14  
 PROPERTIES OF SOIL TYPES AT MERBEIN (cf. FIG. 1)  
 AND DEPTH ADVISED FOR DRAINS

	Rate of Absorbing Water	Depth to light clay	Depth advised for drains
Murray sand .. ..	Very High	No clay horizon	6 ft.
Barmera sandy loam ..	High	5-6 ft.	5-6 ft.
Coomealla sandy loam ..	Moderate	4 ft. 4 in.	4 ft. 4 in.-5 ft.
Coomealla loam .. ..	Moderate	3 ft.	4 ft.
Nookamka sandy loam ..	Moderate	4-5 ft.	4-5 ft.
Nookamka loam .. ..	Low	2 ft.	} Not usually needed
Nookamka clay loam ..	Low	1 ft. 6 in.	
Merbein loam .. ..	Very Low	2 ft.	
Benetook loam .. ..	Low	2 ft.	

The distance between adjacent drains is advised as 66-88 feet for 6-foot drains, and 44 feet for 4-5 foot drains.

first stage in controlling the water-table is therefore to add at each irrigation just the right amount of water to wet the root zone (say the top four feet) to field capacity, and no more. Some very light soils can hold only three inches of available water in the root zone. Anything more is beyond the reach of roots; it does not return by capillarity unless the water-table is close, but it does harm by raising the level of soil water in adjoining land, and may even make the neighbour on lower land suffer while the offender is unhurt. Such soils should therefore be watered lightly and frequently.

Irrigation water commonly runs along the surface down the slope at the same time as it is penetrating the lower horizons at the head of the run. Thus the lighter soil types, which absorb water quickly, must be given it quickly, in order to reach the bottom of the run before the top of the run has received too great an excess. Runs for the same reason must not be too long, 4 to 6 chains being often advised as an upper limit. Every soil type has its own problem. If a relatively heavy, slowly absorbing type lies on the same run below a light, absorptive type, their junction will have a very wet subsoil (see p. 85 for penetration profiles and soakage rates). All this discussion shows the necessity of a good soil map both for lay-out and for drainage.

Crops themselves remove vast amounts of water by transpiration. Thus a temporary water-table at two feet immediately after an irrigation does no



harm in summer since the plants rapidly lower the level. A cover crop of pea or vetch sown between orchard rows during the winter similarly keeps the upper levels dry. Plants differ greatly in the effectiveness of their root systems; lucerne at Griffith kept the water-table down to 10 feet, but orange trees do not reduce the level much below 3 feet.



## CHAPTER VIII

### MECHANICAL COMPOSITION

#### DEFINITION OF FRACTIONS

THE "FINE EARTH" WHICH WE PREPARE FOR STORAGE OR ANALYSIS IS ALREADY very different from the material as it lay in the field; lumps which might have lain unchanged for months have been ground to powder. But there is one feature in common—most of the particles that we see are compound. If we break these particles into the units which make them up, the product may contain everything from grains of sand that just pass the 2 mm. sieve down to the smallest molecule. The mechanical composition of soil records how much of the total weight consists of particles lying between certain size limits over this range. Clearly we can make as many divisions as we please, and at any points we please, but in practice it is convenient to have relatively few fractions and to draw the lines as under:

<i>Fraction</i>	<i>Limiting diameter</i>	<i>Conventional name</i>
I	Greater than 2 mm.	Gravel
II	2 mm. to 0.2 mm.	Coarse sand
III	0.2 mm. to 0.02 mm.	Fine sand
IV	0.02 to 0.002 mm.	Silt
V	Less than 0.002 mm.	Clay

These are the limits adopted in most countries, including Australia; they are known as "International". The five fractions are on a geometric scale, each with a lower limit one-tenth of the next higher fraction. Very often there are only four fractions, I being absent. As we have seen, this fraction if present is weighed and set aside when a sample of soil is prepared for analysis in the laboratory. Organic matter and soluble material, including not only salt but the acid-soluble calcium carbonate, are recorded separately. The American limits are different; for instance, their "silt" includes particles up to 0.05 mm., which is in fact a good dividing line between a soft and a gritty feel.

These names for the fractions have here a conventional meaning. Most people would agree about "coarse sand" (of which dunes and many beaches consist) and about "fine sand", but "silt" has here quite a different meaning from the usual one, which is a fine deposit laid down by a river, high in fine sand and containing as a rule everything but coarse sand. "Clay" also has a distinct technical meaning. The chernozem-like soils of the Wimmera are high in clay, but are so friable that farmers seldom call them clays. The word is



popularly used to describe a sticky soil, whatever its content of the finest fraction may be.

This discussion shows the confusion into which even technical workers have fallen in the use of words. "Sand" can mean either a loose granular soil in the field, or the particles between 2 and .02 mm. of which it is largely composed. "Clay" can mean a tough and plastic soil, (as in Chapter I), or the particles below .002 mm. which give the soil its toughness (as in Chapter III). This ambiguity is most unfortunate, but the context should show which meaning is intended.

Great numbers of mechanical analyses of soils are on record in Australia as well as in other parts of the world. The chief value of a mechanical analysis seems to be that it uses figures instead of words; thus, the contrast between the surface grey loam and the underlying yellowish clay of the podzolic Hallam loam of Southern Victoria, is shown not only by the words clay and loam but also by figures such as these:

TABLE 15  
WEIGHT PER CENT OF OVEN-DRY SOIL

Horizon	Depth	Coarse sand	Fine sand	Silt	Clay	Organic matter
Surface ..	0- 8 inch	3	34	36	21	6
Subsoil ..	18-30 inch	1	9	16	73	1

These figures can be taken in more easily if they are put into graphical form, and this will next be considered.

GRAPHS OF MECHANICAL ANALYSIS

There is no simple way of plotting five values at a time. Organic matter is usually a small fraction of the total weight, and in subsoils it is often less than 1 per cent; so we can exclude it and re-calculate the four "mineral" fractions to add up to 100 per cent. Thus, the re-calculated composition gives:

TABLE 16  
WEIGHT PER CENT OF MINERAL MATTER

Horizon	Depth	Coarse sand	Fine sand	Silt	Clay
Surface ..	0- 8 inch	3.2	36.2	38.3	22.3
Subsoil ..	18-25 inch	1.0	9.1	16.2	73.7



Four values are still not easily plotted. We must sacrifice another piece of information to cut down the values to three. There is no doubt about how to do this—group together the fine and the coarse sand, since the knowledge of how much sand is above 0.2 mm. is not usually important.

We can now plot mechanical compositions in an equilateral triangle, each sample being shown by a single point (Fig. 24), P for the surface and Q for the subsoil.

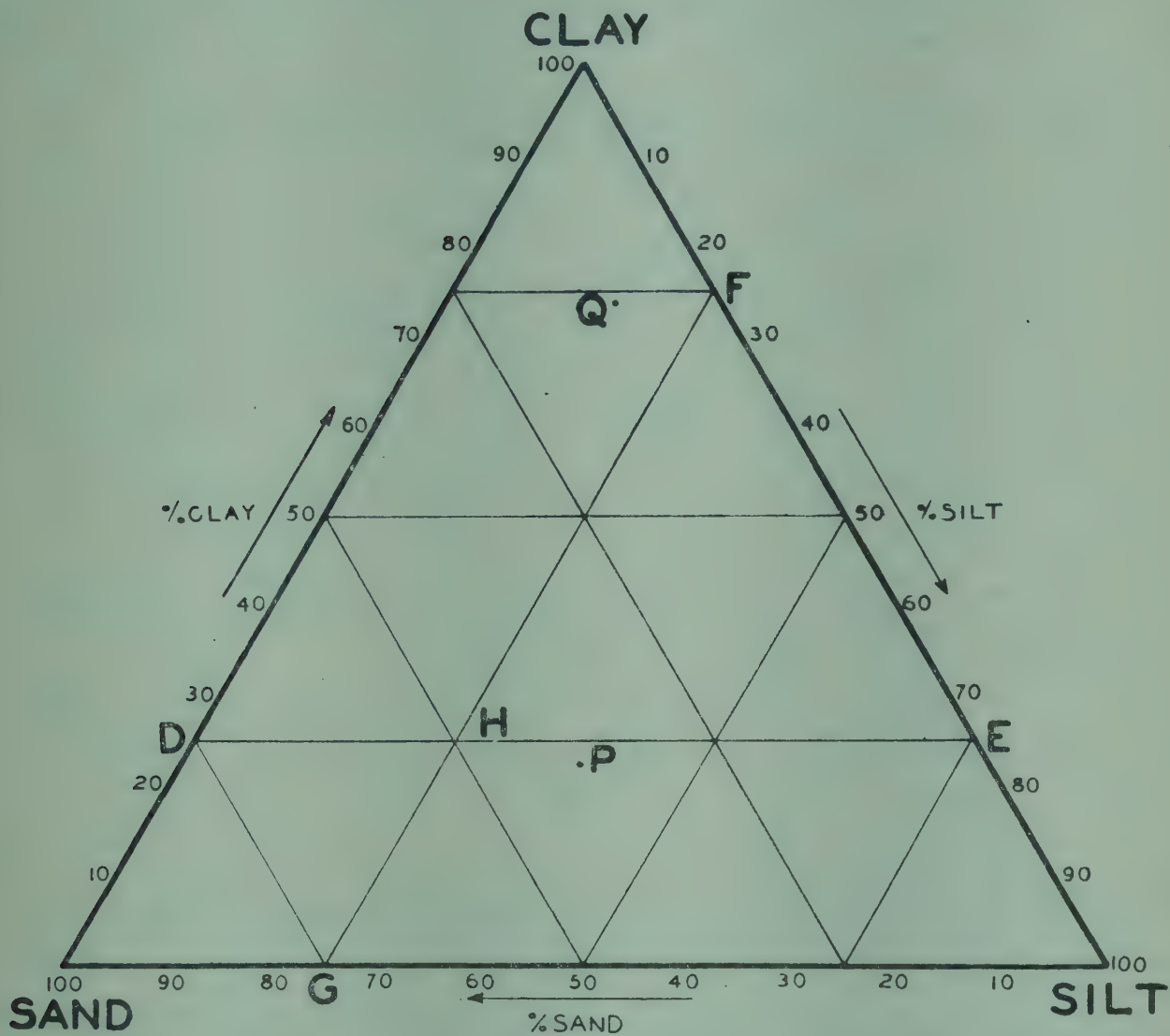


Fig. 24. Triangular system of plotting.

In case this convenient method of plotting is new to the reader, the following explanation may help. All points lying on any horizontal line represent soils with the same percentage of clay. Thus, compositions lying on the base-line "sand" to "silt" contain no clay, those along the line DE contain 25 per cent clay. Again, lines sloping down from right to left represent soils with the same percentage of silt. Thus, all compositions along the line FG contain 25 per cent silt. The point H, where DE meets FG, denotes *both* clay 25 per cent *and* silt 25 per cent; therefore also sand equals 50 per cent. Triangular graph-paper is ruled at intervals of 1 per cent in all three directions. If a dozen samples are plotted, a glance will show which of them is closely related to any other.



## RELATION TO FIELD TEXTURE

The most useful application of this triangular plotting is seen in Fig. 25. The boundaries of any one area—for example, that marked as “sandy loam”—ideally include all those mixtures of sand, silt, and clay which give the feel of that particular texture when worked in the moist state between fingers and thumb (see p. 3).

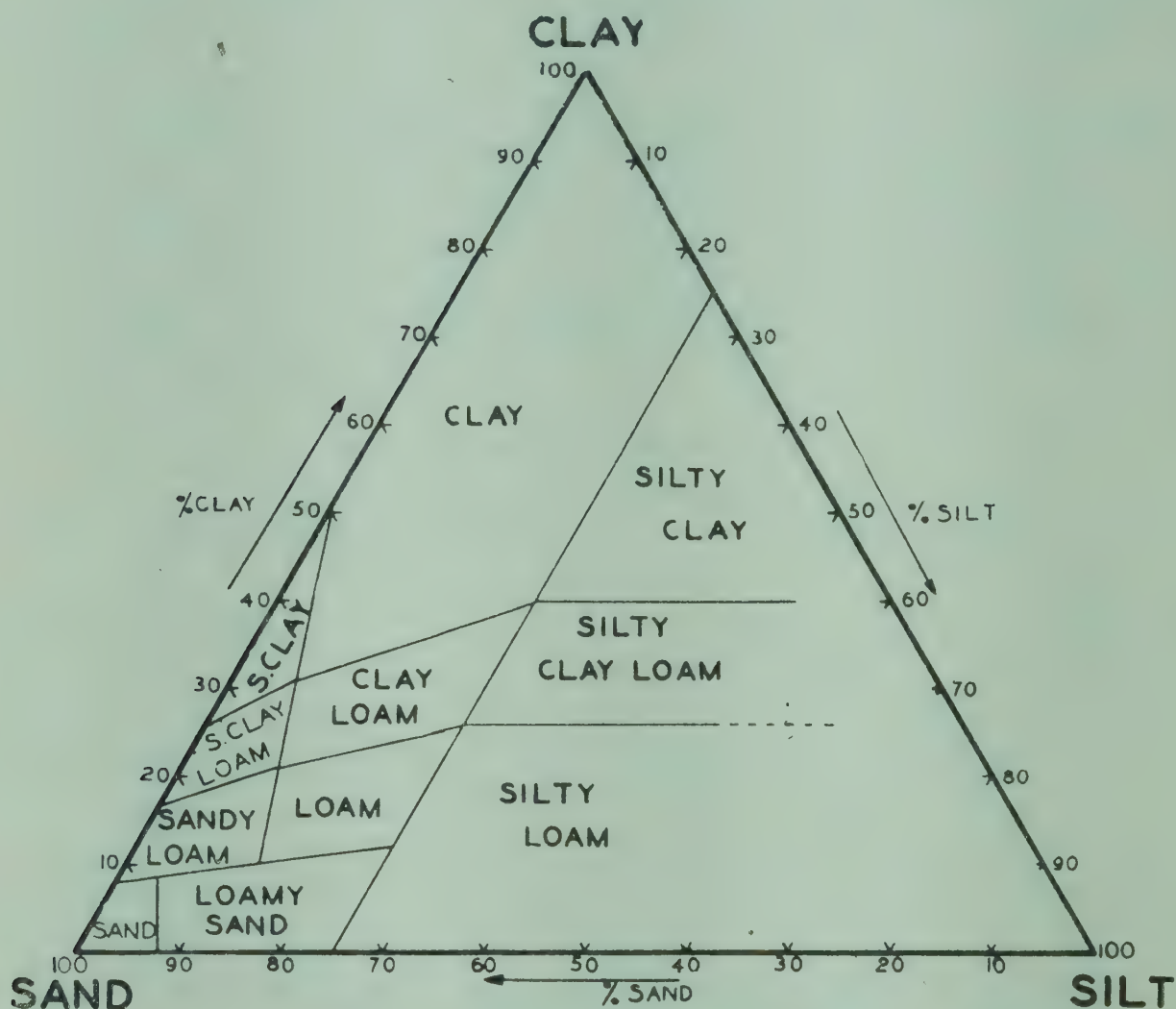


Fig. 25. Soil textures defined in terms of sand, silt, and clay. (C.S.I.R. Bulletin 224.)

Soils with more than 50 per cent silt are extremely rare, so the lower right-hand corner of the triangle is left indefinite. It is interesting to note that of the two non-colloid constituents, silt is more effective than an equal weight of sand in countering the “heavy” feel of clay. (Following the horizontal line with 35 per cent clay, we pass from clay to clay loam as we move from left to right, replacing sand by silt). This is because the particles of the coarser constituent are relatively few; as an extreme case, adding pieces of gravel to the extent of 20 per cent of a clayey soil would obviously not affect its clayey feel.

A mechanical analysis usually confirms the opinion of the surveyor. That being so, one may well ask, why trouble to do it? The analysis is tedious (see appendix for a short method). In fact it seems to be most useful when its result



contradicts the field man's opinion. Some soils show a smaller percentage of clay than would be inferred from the field texture, and others show a higher percentage. In both cases the quality of the clay is responsible for the difference, some clays being particularly sticky and others particularly friable or well aggregated. In either case, what is important is not the amount of clay but the relation of the soil in situ to water and air.

The mechanical composition of the Waite Institute profile is plotted in Fig. 26, and other typical mechanical analyses are collected in Table 17.

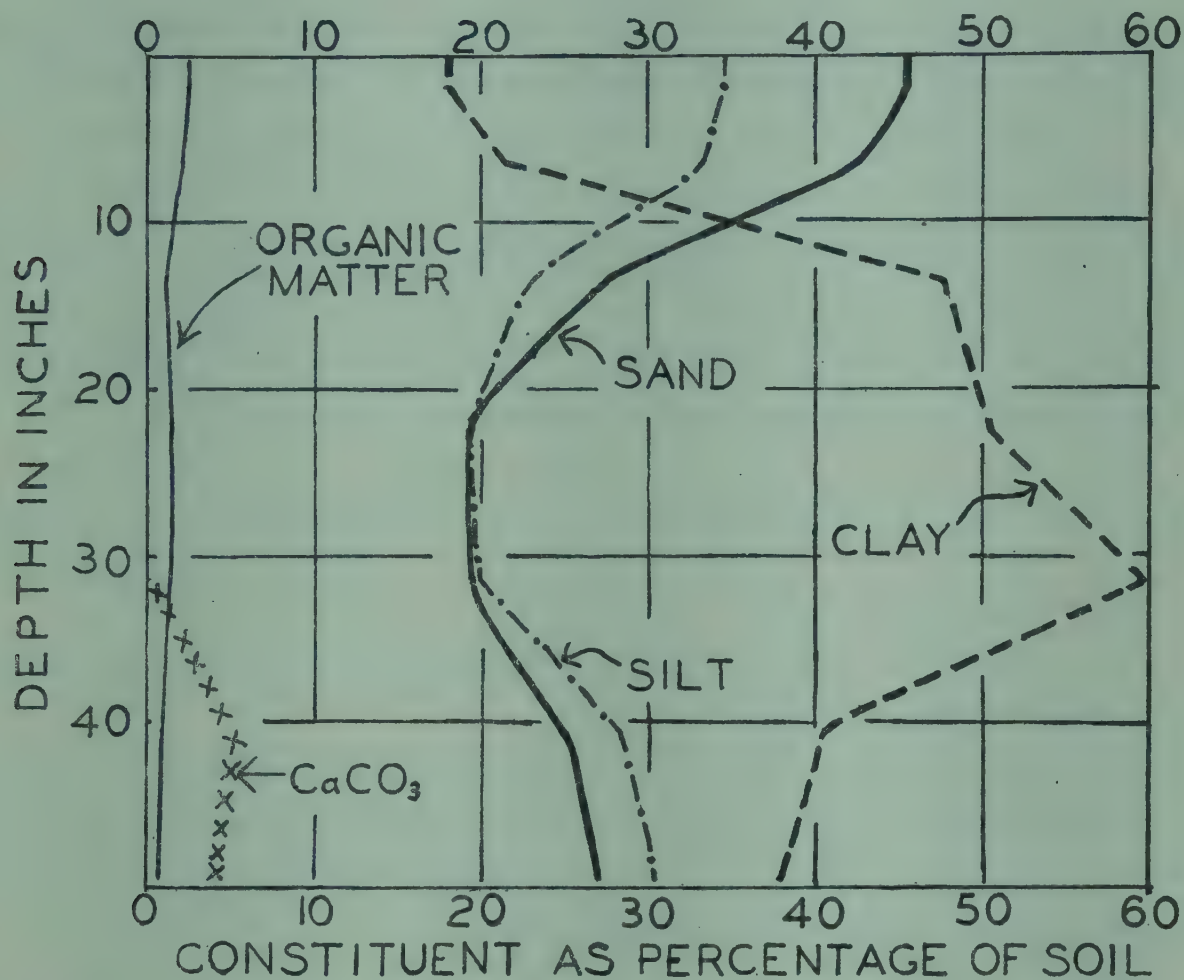


Fig. 26. Profile of red-brown earth formed on colluvium at Waite Institute, Adelaide. (*Trans. Roy. Soc. S. A.* 62, 87.)

i. Murray sand is the desirable type for irrigated citrus. The clay content marks it off from poor blown sand. The very low silt is common to Mallee soils in the eastern states.

ii. The sandy loam of Mount Gambier is excellent physically, being permeable and easy to handle. Its higher content of colloid, inorganic and organic, give it more "body" than Murray sand; its organic matter is an insurance against packing.

iii. Shepparton sandy loam is typical of the hard clod-forming soils of the Goulburn Valley. Both organic and inorganic colloids are too low to form aggregates with the large amounts of fine sand and silt. This may be compared



with an earth road in which enough clay is present to fill the spaces between the coarser particles.

TABLE 17  
MECHANICAL ANALYSES

	I	II	III	IV	V	VI	VII
Coarse sand	43.0	26.5	24.2	12.4	24.9	4.5	8.2
Fine sand ..	46.4	46.4	47.5	18.1	15.7	9.3	11.5
Silt ..	1.4	10.8	17.4	5.3	7.8	7.5	14.5
Clay ..	8.1	10.4	9.4	61.3	48.1	79.0	46.1
Organic ..	0.8	5.7	1.5	n.d.	2.0	1.0	17.6
CaCO <sub>3</sub> ..	0.0	0.2	0.0	0.0	0.8	0.0	0.0

I. Murray sand, surface (C.S.I.R. *Bull.* 137). II. Sandy loam on volcanic tuff, Mt. Gambier (*T. Roy. Soc. S.A.*, 53: 197). III. Shepparton sandy loam (red-brown earth), surface (Vic. Dep. Ag., Soils Sect., *Tech. Bull.* 3). IV. Shepparton sandy loam, claypan below surface (ib.). V. "Black" soil of Wimmera, Natimuk, surface. VI. Krasnozern on older Tertiary basalt, 27-39 inches, Berwick district (*Proc. Roy. Soc. Vic.* 52, 227). VII. Kooweerup peaty clay (Lowmoor peat), surface (*Proc. Roy. Soc. Vic.* 54, 121).

iv. The claypan underlying no. iii is only slowly penetrated by water. This very heavy horizon extends only from 9 to 15 inches depth, and lower horizons are successively lighter, with only 24 per cent clay at 3 feet.

v. The chernozem-like soils of the Wimmera have an excellent structure, the clay being aggregated by the free lime.

vi. The krasnozems on basalt in eastern Australia are high in clay, but the high sesquioxides and high organic matter make them friable and permeable.

vii. In Kooweerup peaty clay the peat dominates; this type is never sticky or cloddy, and is powdery and fluffy when dry.

#### SINGLE-VALUE CONSTANTS

While mechanical analysis yields results which can be plotted as a point, it is often useful to describe the texture of a soil by a single figure. The percentage of clay often serves here. However, this takes so long to determine that scientists have searched for other properties which are related to texture. These are known as "single-value constants". We have already met two of these, namely the sticky point and the moisture equivalent, both of which are correlated with percentage of clay, especially the sticky point. (The sticky point is about 20, 24, 30, and 34 per cent for sandy loams, loams, clay loams, and clays respectively.) One other constant which may be mentioned here is the *Heat of Wetting*, as determined when water is added to oven-dry soil. This is related to the percentage of colloid, and has been used in estimating the best distance apart of drains, as at Merbein; the higher the heat of wetting, the heavier the soil and the nearer the drains should be to one another.



## CHAPTER IX

### SOIL TEMPERATURE

THE ACTIVITIES OF PLANTS AND OF THE ORGANISMS OF THE SOIL DEPEND LARGELY on the temperature. There is a minimum temperature for the germination of the seed of any species; nitrification is halted in winter, and so on. Records of soil temperatures in Australia are scanty; however, a good deal is known about the general principles of the subject, and these will be dealt with here, with illustrations for the most part from the figures obtained at Melbourne University from automatically recording thermometers lying in a sandy loam.

The changing temperature of the land surface is responsible not only for the waves of warmth and cold which pass down into the soil, but also for the temperature of the air. The sun warms the earth, but does little to warm the air, which cannot absorb its relatively short waves (less than a micron long); but the earth radiates longer and less energetic waves (five to twenty microns) which are absorbed by the water-vapour in the air and so heat the whole atmosphere. This effect must be kept in mind although we are chiefly concerned with the soil itself.

#### RADIATION

During the day the surface receives heat from the sun, at a rate reaching a peak at midday. The temperature of the surface may thus rise to over 150°F.; it reaches its maximum soon after midday—not exactly at midday, because the incoming heat from the sun in the early afternoon still exceeds the outgoing heat to the atmosphere and to the underlying soil. The lower air in its turn, receiving its heat from the surface soil, reaches its maximum temperature well after the soil has passed its own peak of radiation, since it too continues for two or three hours to receive more heat than it passes on to higher levels. The lag in the air maximum to about 3 p.m. is a familiar fact, and soil temperatures below the surface show a similar lag.

During the night the surface soil continues to lose heat by radiation to the atmosphere. The net radiation may be reduced by the presence of much water-vapour in the air, or by reflection from clouds, but it is always rapid enough for the surface to become cooler than the underlying soil. So the surface is in turn both warmer and cooler than the lower layers every twenty-four hours.

#### CONDUCTION

In the morning, as soon as the surface soil warms up, it gives some of its heat to the layers below. This passage of heat from warmer to cooler soil is



going on incessantly, and is due to two effects; normal conduction, and movement of water vapour. Conduction is always active; it is least in evidence in dry, loose material, as is shown by the great heat of loose sand in summer and the severe frosts to which the loose peaty soil of drained swamps is liable. Transfer of heat through the movement of water-vapour has been ignored by most writers on the subject, but it must often be important. Water-vapour is bound to evaporate from warm moist soil and condense on cool moist soil, and so to transfer large amounts of latent heat of vaporization from the warmer to the cooler layer.

A wave of heat passes downwards each day; the three-inch level receives this heat more rapidly than it sends it down to the six-inch level (since the rate depends on the temperature gradient), and reaches its maximum temperature at about 3 p.m. This maximum is well below that of the surface; at every half-inch level in the profile as the warm wave arrives it is partly absorbed and partly transmitted, so that the maximum is continually lower with depth and its time of attainment later. At 6 inches the daily maximum is reached at about 6 p.m. but is often very poorly defined, and at about 24 inches all 24-hour fluctuations disappear. The same arguments apply to the upward wave of heat during the night and early morning, the surface being coldest at sunrise and the 3-inch level reaching a much higher minimum at 9 a.m., and so on. These effects are illustrated in Fig. 27B, where the soil is warming up in spring. This

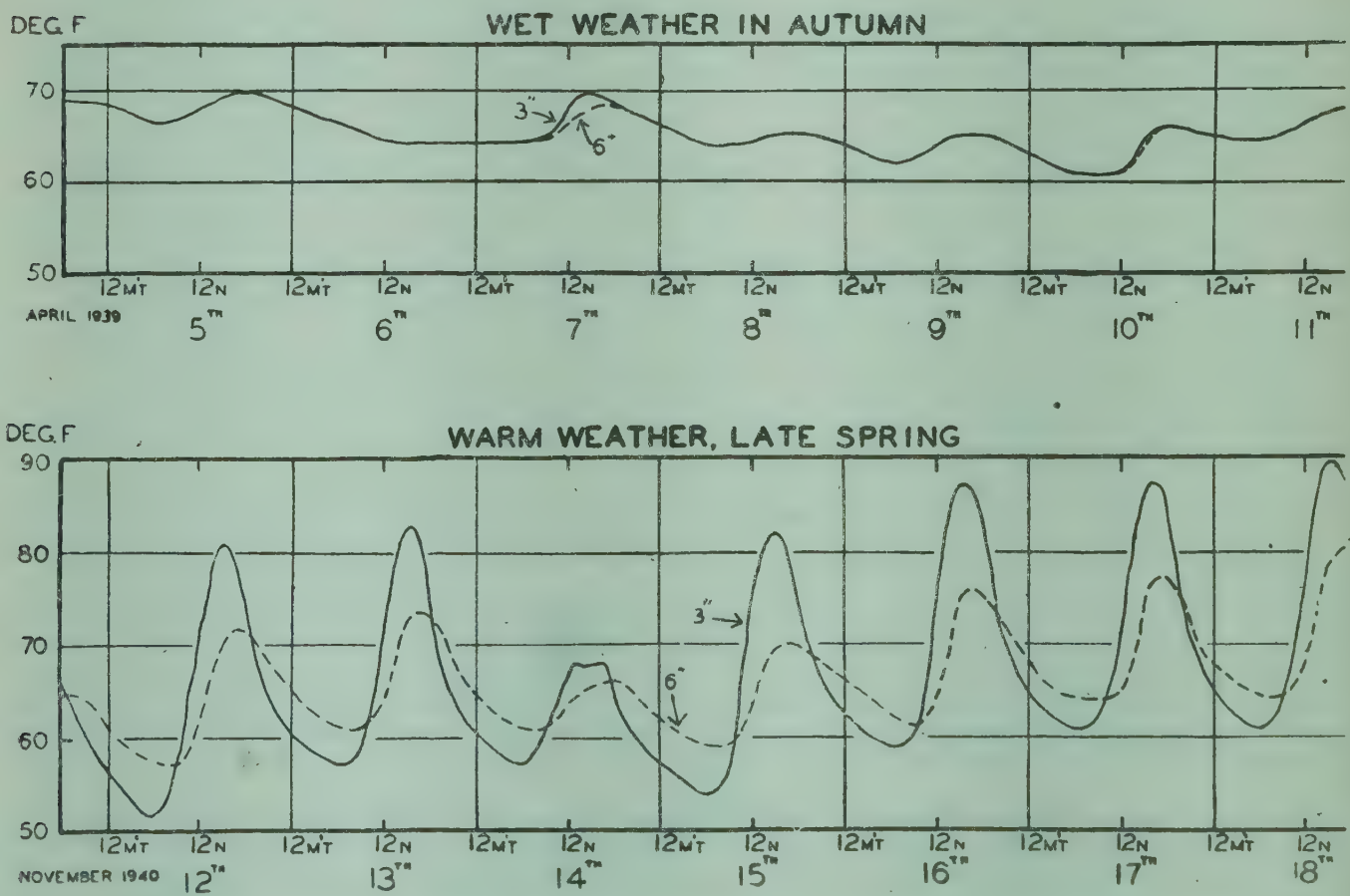


Fig. 27. Soil temperature at 3-inch and 6-inch levels: 27A, Upper; 27B, Lower.



may be compared with Fig. 28A, which illustrates a spell of severe frost (air minimum below  $32^{\circ}$ ) and sunny days.

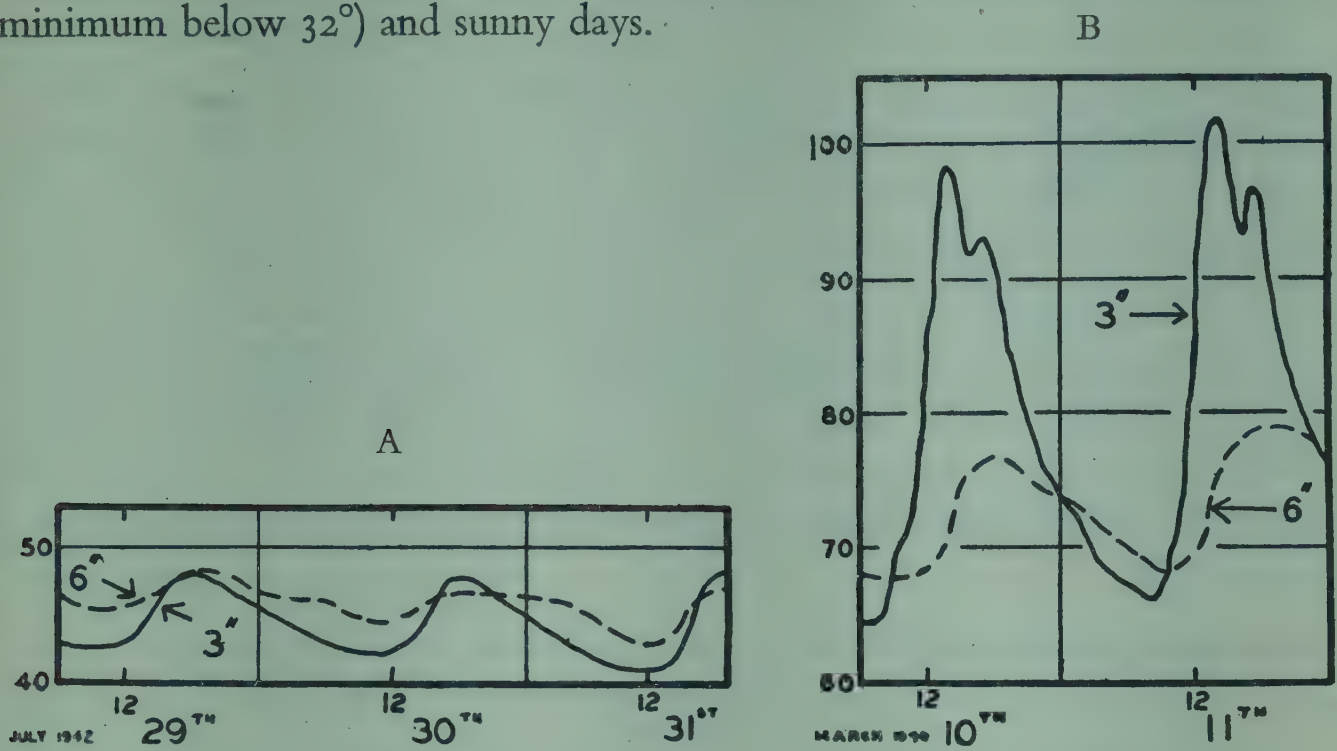


Fig. 28. Effect of (A) frost and (B) shading on soil temperature.

### EVAPORATION

Soil temperature is not determined simply by radiation from sun and soil and the upward and downward passage of warm waves every 24 hours. Evaporation into the atmosphere can also cause an important lowering of temperature, and is responsible for the coolness of wet soils. Taking the latent heat of vaporisation at ordinary temperatures as 650 calories per gram, then the evaporation of even one point of rain (i.e. one ton per acre) means the loss of 650 ton-calories per acre, enough to cool about 1400 tons of moist soil—that is, the surface foot of soil—one degree Fahrenheit.

### RAIN

As a rule, rain cools the soil strongly, bringing it close to its own temperature on account of its high specific heat (1 for water, 0.2 for soil); during a long fall of rain the 3-inch temperature may lie consistently below the 6-inch, as the cold water slowly passes down (Fig. 29A, 31 March, 1940). In June and July, however, rain may warm the soil slightly. This depends on the circumstances. A steady warm fall of tropical origin caused the trace in Fig. 29B; rain from an antarctic depression, however, cools the soil in the usual way. Temperature is steady in wet weather, when radiation to and from the soil is low (see Fig. 27A, where both 3- and 6-inch are at the same temperature as the rain). Wet soils are less liable to frost, because of their high latent heat of freezing, and because they are not so loose as dry soils; the latent heat of evaporation works the other way, but is not so important as the other effects.



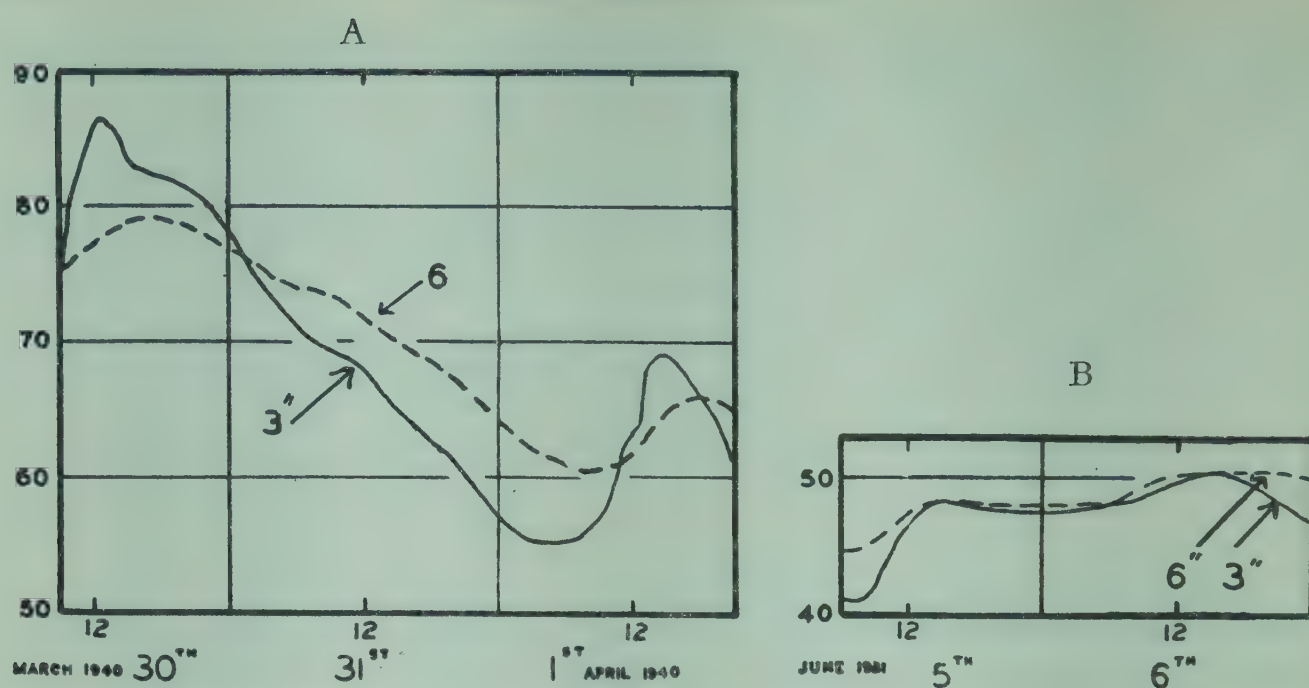


Fig. 29. Effect of (A) cold rain and (B) warm rain on soil temperature.

### SHADING

Since the soil is warmed by the sun and not by the air, shading cuts off the heat most effectively. Fig. 28B shows the lowering of temperature during the afternoon due to two hours shading by a eucalypt. Records taken under bare soil differ greatly from those taken under grass, the 3-inch temperature being two or three degrees lower under grass during the cooler months, and five to seven degrees during the warmer months. Evidently the loss of the sun's radiation by shading during the winter days in Melbourne outweighs the sheltering of the soil from outward radiation during occasional frosty nights. Most published records refer to bare soil since this can be standardized while plant cover cannot. This is unfortunate since we are usually interested in the temperature of soil that is partly or wholly shaded.

### AVERAGE TEMPERATURES

Average soil temperatures depend on the climate, the soil type, the cover, and the slope. Slopes facing north are warmer by day than level ground, since the sun's rays are more nearly at right angles, but there are no local figures to show the extent of this effect. Soil type is of most importance in affecting retention of water; sandy soils are dry, so are both warmer on the average and more subject to extremes at the surface than the heavier soils; but there are no local figures for illustration.

*Cooler Months.* On level ground at Melbourne the 3-inch and 6-inch mean temperatures under grass are close to the mean air temperature during the cooler months, being a little lower during the winter. The soil is never very cold except in the top inch. The coldest ever recorded at 3 inches is 38°, and at 6 inches 42°. Another interesting feature in winter is that the deep subsoil is a



little warmer than the surface, and so slightly more favourable for deep-rooting plants (cf. figures for Adelaide, Table 18).

*Warmer Months.* The soil is warmer than the air during the warmer months, especially during dry weather. The monthly soil temperatures in Melbourne also vary much more widely than the monthly mean air temperatures, in which a departure of three degrees from normal is extraordinary. For example, in the two months January 1943 and January 1944, the 3-inch means under short grass cover were  $72.5^{\circ}$  and  $77.6^{\circ}$  respectively, while the mean air temperatures were 69.1 and 68.6. The reason for this contrast lies in the rainfall, 283 and 74 points respectively. The frequent spells of fine sunny weather with cool southerly winds are largely responsible for the greater warmth of the soil as compared with the air in some seasons.

Some of the relevant records are given in Table 18. The Melbourne figures for soil under grass are based on only three years' readings, and are therefore liable to error. However, the air temperatures during the months reported were normal, except for April, for which the values may be two or three degrees too low.

TABLE 18  
MEAN TEMPERATURES IN SOIL AT MELBOURNE AND ADELAIDE  
COMPARED WITH MEAN AIR TEMPERATURES

	Depth		Feb.	Apr.	July	Oct.
Melbourne . .	3 in. (under grass)	Max.	77.8	61.9	48.8	61.4
		Min.	67.4	56.3	45.8	56.2
		Mean	72.6	59.1	47.3	58.8
	6 in.	Mean	71.2	59.6	47.2	58.4
	Air	Mean	67.6	59.5	48.8	57.7
Adelaide (Waite Inst.)	6 in. (bare soil)	Mean	77.9	65.4	51.8	64.6
	24 in.	Mean	73.2	66.3	53.6	61.1
	Air	Mean	70.9	62.7	51.4	59.8







PART III  
THE CHEMISTRY OF THE SOIL







## CHAPTER X

### GENERAL CHEMICAL CONSIDERATIONS

#### THE NUTRIENT ELEMENTS

THE MAIN INTEREST OF CHEMISTS IN THE SOIL IS THE IMMEDIATE ONE OF STUDYING those elements which plants need for growth. We know that at least 15 elements are essential for the higher plants: they are as follows:—

Carbon, hydrogen, oxygen, nitrogen, phosphorus, potassium, calcium, magnesium, sulphur, iron, manganese, copper, boron, zinc, molybdenum.

Carbon, hydrogen, and oxygen are derived from air (carbon dioxide and oxygen) and from water. The others are supplied by the soil, though some plants use the nitrogen of the air (see Chapter XII). All 15 elements must be available in ample amounts in order to produce maximum growth. If any one is deficient, even ideal amounts of the other 14 cannot make up for it. If more than one is deficient, nearly always the deficiency of one element is more serious than that of any other; the element in shortest supply must be added before the plant can make more growth. Such an element is called the *limiting factor*. In Australia, hydrogen (i.e. water) and phosphorus are naturally the commonest limiting factors.

We can show the need for each of these elements by growing plants in water culture and supplying in solution every element except the one in question. Using ordinary reagents such as  $K_2SO_4$ ,  $KH_2PO_4$ ,  $MgSO_4$ ,  $Ca(NO_3)_2$ , etc., it is easy to show the need for N, P, K, Ca, Mg, S, and perhaps Fe, but the last five on the list (Mn, Cu, B, Zn, Mo) are needed in such small amounts that ordinary culture solutions commonly contain ample of them as accidental impurities in ordinary distilled water and reagents. Expert work, however, with scrupulously pure materials has shown that they are all essential. Deficiencies of all of these elements have been observed in the field, and we are gradually learning to recognize the symptoms of deficiency and to add the necessary element or change the method of management so as to avoid any further trouble. Thus, nitrogen-starved plants are yellow, as may often be seen in oat crops in the winter; potassium-starved plants often show a brown edge to the leaf, which has led to the name "leaf-scorch". Observations of plants in synthetic culture solutions in greenhouses have helped greatly in diagnosing trouble in the field.<sup>1</sup>

<sup>1</sup> *Hunger Signs in Crops* (American Society of Agronomy and National Fertilizer Association) contains coloured plates of deficiency symptoms of many plants. Similar work is available in T. Wallace, *The Diagnosis of Mineral Deficiencies in Plants* (H. M. Stat. Off.



Every one of these elements (omitting here C. H. and O) passes through a cycle of changes in the soil and the plant. From solution in the soil-water it passes to the root, thence to the leaf, flower and seed, and thence back to the surface of the soil, which it may reach directly, or in the excreta or even the body of an animal that eats the plant, or in the ash if the plant is burned. Once at the surface of the soil it may stay near its point of arrival but change into an insoluble form, or it may be washed downwards by the rain and either be left in the subsoil to be tapped again by roots or washed right away into the drainage water. Further, at any stage the cycle may be interrupted to pass through microbial protoplasm instead of a higher plant. This cycle of changes has to be borne in mind for all these elements. The best example of all, and the most thoroughly studied, is nitrogen, which is discussed in Chapter XII.

While as chemists we are mostly concerned with those elements which may have to be added as fertilizers, we are also interested in another aspect—the amount and movement of elements which are important in soil but which are of trivial importance to plants (like Si and Al) or which are present in far greater amounts than they are needed (like Fe and Mn). This aspect is not so close to immediate problems as the one just described. Yet the two are often closely connected, and the fundamental knowledge of how the profile reached its present state often turns out to be useful in providing a background and helping us to understand our practical problems better.

Table 19 shows the average total composition of a number of soils, compared with the composition of an oat crop. Plants differ greatly in composition according to the species (e.g. dicotyledons are low in Si, many legumes are high in Ca) and those of the same species vary with the environment, so the figures have no claim to exactness.

#### THE USE OF CHEMICAL ANALYSIS

The way to find whether a soil needs any treatment is to try it out in the field. However, field experiments cost time and money. Crops themselves may show symptoms which indicate the need for a nutrient, but it is generally better to give them that nutrient before they show any signs of deficiency. We may try to find what nutrients are deficient, and to what extent, either by tests with pots in a greenhouse, or by laboratory methods. In a pot test we compare the growth of our experimental plants with and without an added nutrient. This has the advantage of being like a small-scale field test, in which we can avoid the uncertainties of the weather; on the other hand, a pot test is cumbersome and takes a long time, and needs to be cautiously interpreted since the natural profile has been destroyed by its transference to the pot. There



remain the chemical analyses of the "fine earth", by which chemists have tried to test the ability of a soil to supply the necessary elements.

TABLE 19  
AMOUNT OF ELEMENTS PRESENT IN SOIL  
AND IN MATURE OAT CROP

Element	Si	Al	Fe	K	Na	Ti	Ca	Mg	N
Total in soil, %	36.0	6.9	3.5	1.5	0.6	0.6	0.5	0.4	0.1
Total in crop (dry matter) %	1.0	tr.	.01	.6	.04	tr.	.18	.10	1.2

Element	P	S	Mn	B	Zn	Cu	Co	Mo
Total in soil, p.p.m.*	600	500	500	20	10	5	5	1
Total in crop, p.p.m.	1800	1800	40	3	15	3	.05	1

\*p.p.m. = parts per million.

The elements down to Mn are the most copious in the soil in that order. They are an average of complete analyses taken from *Soils and Men* (p. 778). The other figures are taken from various sources, mostly in Australia and New Zealand. The last five elements are of biological interest and do not follow in order of copiousness in soil (Cl, Ba, F are all more plentiful than these). The figures for these five are of extracts with concentrated HCl, not total analyses of soil.

Most people, including farmers and gardeners, have an exaggerated idea of the value of a chemical analysis of soil. In fact, the results of analysis up to the present time have not fulfilled the high hopes with which chemists set out last century. The problems may be divided into two; on the one hand, whether a soil needs lime, needs no lime, or already has too much; on the other, whether a soil needs other nutrients. The first problem is more often easily solved than the second. It is dealt with in Chapter XIV. The second problem, the need for individual nutrients, is dealt with here.

When chemists began soil analysis a century ago, their first step was to determine the amount of the element extracted by boiling concentrated hydrochloric acid. Thus it was hoped one could convert the result into pounds per acre, using the convenient assumption that the top  $6\frac{1}{2}$  inches of an acre weighs 2,000,000 pounds, and say something like this: "This soil contains 3,000 pounds of potassium in the top six inches of an acre; a 2-ton cut of oaten



hay removes 30 pounds; therefore the top soil contains enough potassium for 100 good crops of hay". After reckoning the reserves in this way, the next step was to suggest that all soils containing less than so much per cent of the element (0.2 for potassium, 0.07 for phosphorus) needed an additional application as fertilizer. (In fact, fusing the soil with sodium carbonate in platinum may show that substantially more of the element is present than is extracted with HCl, but such resistant material is commonly ignored, especially since such fusions are too tedious for general use.)

This crude attack has had some successes with some elements, mostly where the soils studied had never been treated with fertilizer. One example was on poor sandy country in the south-west of Western Australia, where numerous pine plantations failed for lack of phosphorus, and where a good dividing line was drawn on the basis of HCl extracts; on soils with less than 0.017 per cent of P *Pinus radiata* would not grow well, and with less than 0.007 per cent P *Pinus pinaster* (with a lower requirement) also grew poorly. However, the general relation with results in the field is poor. Some soils with as little as .1 per cent of potassium soluble in the concentrated acid turned out to be better supplied (for immediate purposes) than others with .3 per cent or more. Manganese gives even more striking examples. The minute amounts of this element required for healthy growth (about 1 ounce per acre) are better supplied by many acid soils with as little as .005 per cent of Mn soluble in strong acid, than by some alkaline soils with as much as .1 per cent.

Chemists came to realize that the concentrated acid dissolved elements, not only from useful compounds, but also from compounds which the roots could not use; so they turned next to gentle extractants such as dilute citric acid and very dilute sulphuric acid at room temperature—which of course dissolved much smaller amounts. One of the new recommendations, for example, was that a soil should yield 0.002 per cent of P and 0.01 per cent of K to a cold solution of 1 per cent citric acid, failing which the respective fertilizer should be added. Refinements were later added, in the form of higher requirements for some crops, such as vegetables. This gave greater success in practice, though far from complete success. At this stage of development a distinction is made between the quickly available fraction of each element and the unavailable—or better, slowly available—remainder. This leads on logically to the point of view set out in the next section.

#### CAPITAL AND INTEREST

The total capital of an element in the soil at any moment consists of several categories, ranging from the most easily available to the most inert. While every gradation exists between these extremes, it is useful to think in terms of



three categories—viz., a small first-class source (A) which liberates the element rapidly to solution; a larger second-class source (B) which liberates it more slowly; and a third-class source (C) which makes up most of the total capital and weathers very slowly indeed. The argument is best shown in figures. Suppose that the respective rates of interest (or better, *delivery*, since the capital is used up) for sources A, B, and C of phosphate in a soil are 50 per cent, 5 per cent and 0.1 per cent per annum. Then the total amount of phosphate becoming available per acre in one year might work out like this:

TABLE 20  
DELIVERY OF NUTRIENT FROM DIFFERENT SOURCES

Source	Capital, lb. per acre	Rate of Delivery per cent	Amount delivered p.a. in lb. per acre
First class (A) ..	20	50	10
Second class (B) ..	100	5	5
Third class (C) ..	1000	0.1	1

Besides the weathering which produces this soluble material, another process works in the opposite direction—namely, the reversion of high-grade material into low-grade. The atoms of amorphous or colloidal particles (with a large area of surface per unit mass) slowly rearrange to form definitely crystalline masses of much smaller surface. This process is familiar in analytical chemistry and is called *ageing*. Freshly precipitated aluminium hydroxide, for example, redissolves easily in dilute acids, but the longer it remains on the filter-paper the harder it is to dissolve. Thus every year some of A reverts to B and some of B to C. At equilibrium, with no leaching and no application of fertilizer and no removal of crops, we get the situation in the next table. If all the soluble phosphate (or whatever the nutrient may be) returns to A, then A must lose 6 lb. to B each year in order to remain at 20.

TABLE 21  
BALANCE SHEET OF DIFFERENT CLASSES OF SUPPLY

Source	Capital	Delivered to solution	Recovered from soln. (total of previous column)	Reverted A to B	Reverted B to C
A ..	20	- 10	+ 16	- 6	..
B ..	100	- 5	..	+ 6	- 1
C ..	1000	- 1	..	..	+ 1



Thus the balance is completed by letting A degrade at the annual rate of 30 per cent and B at 1 per cent.

These tables are entirely imaginary. No one has yet separated an element in the way described, nor determined its rate of interest; and as already explained there is no sharp line of demarcation between A and B, or B and C. The old reliance on HCl implied that all soils have a constant rate of supply from the gross capital. Tenants' agreements in England also assume a universal rate of degradation for each essential element. They reckon that two-thirds the value of the phosphorus, none of the nitrogen, and half of the potassium applied as fertilizer remain after the first crop is harvested.

### *The Soil Solution*

It is possible by using high pressures to squeeze out some of the water that is held by the soil. This water, which contains dissolved matter, is called the *soil solution*, in contrast to a *soil extract*, which is obtained when soil is shaken with excess water, as is done when determining the total amount of an ion that is completely soluble, especially nitrate or chloride. The elements present in the soil solution are obviously a first-class source for plants. The main cations present are calcium, sodium, and magnesium; the main anions are bicarbonate, sulphate, and sometimes nitrate and silicate. The study of soil solutions has had little success as yet. The methods of obtaining them are awkward and not yet standardized. Besides, some elements in which we are most interested, especially potassium and phosphorus, occur only in minute amounts in solution, so that we come back to the problem of estimating how rapidly the solution will become replenished from other sources.

### RIVAL CHEMICAL TESTS

Dilute citric acid has just been mentioned as a routine reagent for determining whether a soil needs an application of fertilizer. This test works for many soils, but there are also many cases in which it fails to provide the correct advice. Innumerable other tests have been suggested for determining the first-class or the second-class reserves of a soil, particularly in phosphorus and potassium. For instance, ammonium bisulphate solution of pH 3 (Truog's solution) is a favourite reagent for phosphorus in North America, and has the advantage that the extract is very easy to analyse. With all of these tests, however, there are far too many doubtful cases. In this doubtful zone, the adviser may be right or wrong, but he improves his chance of giving useful advice by knowing the soil types of his district and their record in relation to his test. So the merit of any one test may be simply that it has often been used before on



that soil and in that climate, and an experienced man will therefore interpret the result with a fair chance of success.

Weakly acidic solutions were first suggested as extracting agents last century when it was believed that roots excreted dilute acids into the soil. The effect of a root on the soil can be expressed more satisfactorily today in terms of an exchange of ions between the root hair (which has a negative charge) and the soil colloid in contact with it, thus:—



The metallic ion  $\text{M}^+$  exchanges places with the hydrogen of the root; this ion then moves inside the root and eventually another hydrogen appears outside and the process continues. Thus the plant takes metallic ions directly from the soil colloids, the active hydrogen ions for the process being derived from the energy of respiration. A dilute acid extractant thus simulates the action of the root according to the newer ideas as well as to the older ideas. Phosphate is a special case (see Chapter XVI). The intake of anions in general is a separate problem.

Besides extracting the soil with reagents, some laboratories in Europe measure the amount of nutrient extracted from a sample of 100 gm. of soil by 100 rye seedlings. Again the same argument is used; the seedlings are analysed, and if they contain less than 2 mg. phosphorus above what the seed contained, the soil needs additional phosphate. This method (named after its inventor Neubauer) works about as well as the others.

In Australia we have little experience of dilute-acid extractions and less with Neubauer tests, but they will become more important as our main deficiency—in phosphorus—becomes satisfied.

## OTHER ASPECTS

### *Subsoil*

The soil lying more than 6-8 inches deep is commonly neglected in all these studies. This seems at first unreasonable, since roots undoubtedly travel well below the ploughed layer. However, the sub-surface layer is commonly very low in nutrients (cf. pp. 46, 178), so it can generally be safely ignored. The deeper subsoil, as the parent material is approached, may be richer, but is usually also poor. The deeper layers are naturally more important for trees and other perennial plants than for annual crops.

### *Chemistry and Structure*

The structure of the soil is also most important in studying chemical properties below the ploughed layer. All our common tests ignore the general



existence of structural units, which have different chemical properties inside and outside. An element may be concentrated on the outside of an aggregate and so be available in far greater amounts to roots than appears from the analysis of fine earth, in which the aggregates have been destroyed. One essential line of future development in our science is the application of microchemical tests to portions of the natural aggregates.

#### *Difference between Plants*

Plants differ markedly not only in the extent of their roots but in their ability to obtain nutrient elements from the same source. Thus lupins can use phosphorus of a lower class than subterranean clover can; timothy, a grass much commoner in U.S.A. than here, can obtain potassium from lower-class sources. Such individual behaviour must be kept in mind when interpreting analyses.

#### ADDITIONAL KNOWLEDGE NEEDED

These tests are all arbitrary, and are not highly scientific. We simply hope that those atoms of phosphorus which are dissolved by citric acid (or whatever it may be) are also available to roots. We can go much further than this, however, and learn something about the individual chemistry of each element in the soil. This knowledge is valuable in interpreting routine analyses, and in deciding on the best treatment for overcoming any deficiency. This will be the substance of the following chapters. Meanwhile, it can be said in general that the reserves of chemical wealth are of two kinds—the colloid and the unweathered minerals. The minerals are discussed in Chapter XIII. The colloid is important because of its large surface, and it is common (though by no means universal) to find the richer soils higher in colloid. This principle is generally accepted for potassium, and it also holds for other elements.



## CHAPTER XI

### ORGANIC MATTER

All soils contain organic matter—that is, carbon compounds other than carbonates. This is necessarily so, since the soil supports the life of plants and must therefore contain their remains. A soil, however, is not a storehouse of dead cells, but contains great numbers of micro-organisms which act on these cells, convert them into a variety of products, and build their own cells from some of these products. The resultant mixture is very complex.

The total amount of organic matter may be anything from nearly 100 per cent (in a “highmoor peat”) to under 1 per cent. All soils dealt with in this book, except the peaty types, contain less than 20 per cent organic matter.

The organic matter of the soil is of great interest for three main reasons. It is the seat of microbial actions. It can have a profound effect on physical properties. It is closely related to the nitrogen nutrition of the plant. These aspects will be dealt with separately.

#### MICRO-ORGANISMS OF THE SOIL

The micro-organisms of the soil are of great importance, since in the course of carrying out their own vital reactions they may either liberate or absorb the simple ions which plants use. Their products may also influence the weathering and development of the soil. For example, locally produced nitric or sulphuric acid (see below) may attack a mineral; bacteria can also be responsible for concentrations of iron and manganese.

#### *Classification*

The two main groups of micro-organisms in the soil which bring about chemical changes are bacteria and fungi, the most important of which have a world-wide distribution. Biologically, bacteria and fungi differ in important respects; but when we are concerned with the physics and chemistry of soil, we may often ignore these differences and classify rather in terms of chemical relations. From this point of view the main difference between the two groups is that fungi are generally more tolerant of acidity than bacteria. Two other groups—protozoa and algae—are also universally present, but little is known of their effects on reactions in the soil.

*Source of Carbon:* The most important distinction among micro-organisms for our present purpose depends on the source of the carbon with which they build their cells. Some bacteria resemble plants in using only carbon dioxide for this purpose. All other bacteria, together with fungi, use organic molecules



such as glycerol, or alanine.<sup>1</sup> The former group need considerable energy to reduce CO<sub>2</sub> to compounds where carbon is joined to other carbon atoms or to nitrogen, and which can be used for the synthesis of protoplasm, and they obtain this energy from the oxidation of simple materials such as sulphur. For example, it takes 3,900 calories to produce a gram of glucose from CO<sub>2</sub> and the complete oxidation of 0.9 gm. of sulphur produces the same energy. Therefore, if all the chemical energy set free by oxidizing sulphur could be used for building up organic molecules, these bacteria would need less than a gram of sulphur to form a gram of glucose (or any similar compound) from CO<sub>2</sub>. In fact they use about twenty times as much sulphur as this, their mechanism being only about 5 per cent efficient. Such bacteria are called *autotrophic* (i.e. "self-feeders") and may be compared with plants, which also build complex molecules from CO<sub>2</sub> as their sole source of carbon, and obtain the necessary energy from sunlight. All other bacteria are called *heterotrophic* ("feeding on others"); together with fungi, they rely to varying degrees on compounds already synthesized by other organisms—namely, plants and autotrophic bacteria. These groups are complementary to each other and will be considered in turn.

(1) *Autotrophic Bacteria*: The most important species are as follows:—

(a) *Nitrifiers*. These belong to two groups, those which oxidize ammonia to nitrous acid and those which oxidize nitrous to nitric acid,



The first reaction sets free 79,000 calories for every 17 gm. of ammonia, the second sets free a further 31,000 calories. Several organisms can carry out each of these actions, and some of them tolerate moderate acidity, but a pH of about 4.5 appears to limit their activity. The acid-tolerant species were not discovered till the 1930's, which accounts for the common belief that lime is necessary for nitrification. Lime may hasten the process, but is not indispensable.

(b) *Sulphofiers*. These oxidize sulphur and some of its compounds to sulphuric acid, often by way of thiosulphuric acid (H<sub>2</sub>S<sub>2</sub>O<sub>3</sub>) as an intermediate product.



One of these, *Thiobacillus thiooxidans*, is very tolerant of the acidity which it produces, and thrives even at pH 1 (tenth-normal acid). Apparently, whether this species is present or not, sulphur will always be oxidized by bacteria when mixed with a warm and moist soil.

<sup>1</sup> Glycerol is CH<sub>2</sub>OH. CHOH. CH<sub>2</sub>OH, alanine CH<sub>3</sub>.CH(NH<sub>2</sub>).COOH.



(c) The two above groups are the most important. Other organisms can obtain their energy by oxidizing ferrous compounds to ferric, manganous to manganic, or hydrogen gas to water.

(2) *Heterotrophic Bacteria and Fungi*: These attack the dead tissues of plants or of other organisms, and break the large molecules of proteins and carbohydrates through a chain of reactions into successively smaller units, forming simpler compounds such as citric acid, and liberating phosphate and metals (such as potassium and calcium) from their organic combinations. They either absorb the simple organic molecules or oxidize them completely to  $\text{CO}_2$ ,  $\text{NH}_3$ , and  $\text{H}_2\text{O}$ . The cycle of changes is summarized in Fig. 30.

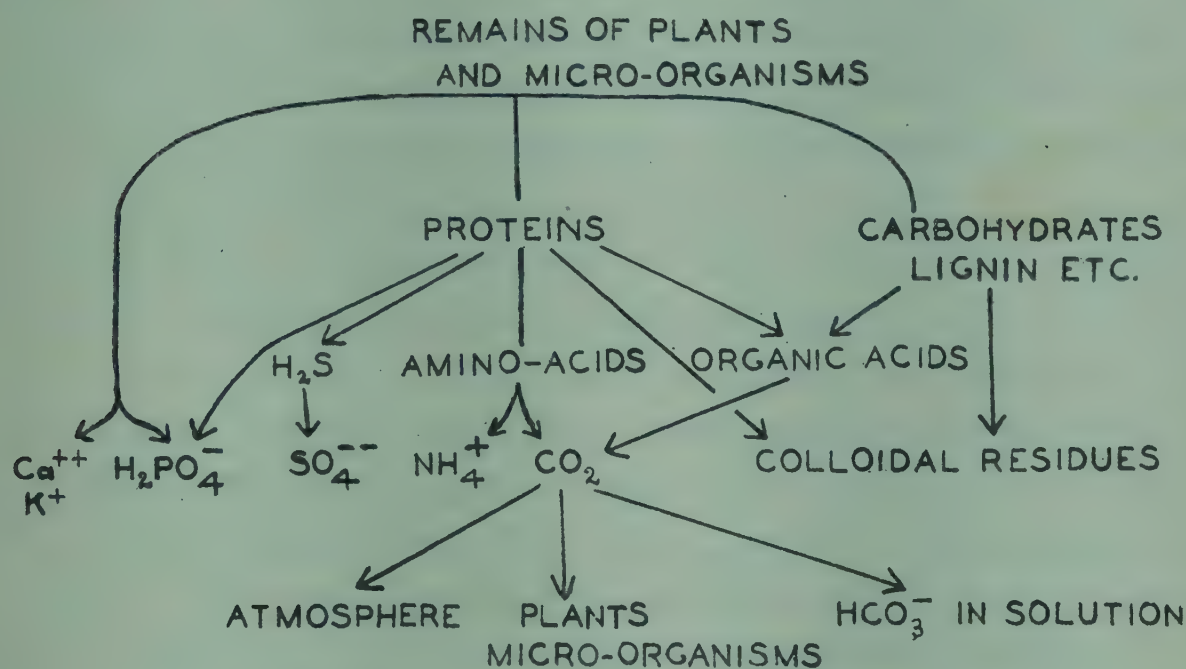


Fig. 30. Changes of organic matter in soil.

The number of reactions here is enormous; not only are there many species of organisms, but each organism can perform several reactions, the particular one depending on the circumstances. Only a few salient points need be noted.

(i) The majority of the reactions are beneficial to plants; it is clearly essential that organisms should break down dead tissues and release the simple ions which plants use. Some products of decomposition are toxic—for example, phenol; but some bacteria can act as scavengers and oxidize these away before they accumulate. Besides these desirable species, some disease-bearing organisms are also present in soil; but the study of these belongs rather to plant pathology than to soil science.

(ii) Some micro-organisms live in *symbiosis* with plants. These colonize the roots and appear both to give and to derive benefit from the association. One such type, the *mycorrhizal* fungus, is common in poor and sandy country; little is known yet about its chemical contribution to the plant. The other type,



*Rhizobium*, has been intensively studied. These organisms fix atmospheric nitrogen in association with leguminous plants, and are dealt with in Chapter XII.

(iii) Some bacteria (but not fungi) can live without gaseous oxygen. These are called *anaerobic* bacteria. They may be further subdivided into a few species which cannot tolerate oxygen and are known as obligate anaerobes, and a great number of species which can adjust their metabolism to live either with or without oxygen. All these organisms need an oxidizing agent to carry out oxidations which can provide them with energy. Such anaerobic oxidizing agents include ferric and manganic oxides (which are reduced to give the bivalent ion), nitrate (which may be used for its oxygen as well as for its nitrogen) and sugars (which are high in oxygen). A typical product of anaerobic oxidation is butyric acid,  $C_4H_8O_2$  (containing 36 per cent oxygen by weight), which may be compared with the aerobic product citric acid,  $C_6H_8O_7$  (58 per cent oxygen by weight). Anaerobic reactions produce less energy than aerobic since they use less oxygen, so they need temperatures 5-10 degrees centigrade higher to go with comparable speed. A simple experiment on anaerobic activity is described on p. 198.

The smell of anaerobic processes is characteristic and very different from the pleasant smell of fertile soil. Little is known of the source of this pleasant smell; possibly an observer with a keen sense of smell might learn to recognize several degrees of goodness of drainage in soils, as well as other differences.

The obligate anaerobes present a curious problem in chemistry. It appears that what poisons them is not oxygen itself but hydrogen peroxide, which is formed from oxygen by reduction ( $O_2 + 2H \rightarrow H_2O_2$ ). Most organisms contain an enzyme which destroys hydrogen peroxide, converting it into the harmless oxygen. Obligate anaerobes have no such enzyme.

(iv) Two common terms, *putrefaction* and *fermentation*, have the following meaning. The former refers to the decomposition of nitrogenous material with the liberation of ammonia, the latter to the decomposition of non-nitrogenous material.

#### *Numbers of Micro-organisms*

Many attempts have been made to count the total number of bacteria in a sample of soil. The number in a fertile soil of temperate climates is of the order of  $10^9$  per gram; this works out at about 0.1 per cent of the weight of the soil. The number is lower in subsoils and less fertile soils, and in dry climates. There is no local information on bacterial numbers, and in any case such knowledge does not seem to have found much application elsewhere.



*Relation to Temperature*

Bacteria generally reach their greatest activity between 70 and 90° F., and are inert below 50°. Since water is as necessary for them as for plants, we would expect to find autumn and spring to be the periods of greatest activity, and this appears to be so. Some organisms thrive at higher temperatures (120° F.) and these are called *thermophilic*.

## COMPOSITION OF ORGANIC MATTER

The organic matter of normal soils throughout the world has much in common. It is dark brown to black, and is mostly of colloidal size. While its presence is easily recognized, it cannot be separated from the rest of the soil without being drastically changed. On this account, there is still much confusion and controversy as to the best way of picturing it. It is doubtful, however, if one can do better than accept the simple point of view which is set out here and which is due to Waksman.

The material which is used by the micro-organisms consists of the residues of plants and other organisms. The more easily attacked components of these—starch and reactive proteins—quickly disappear; it follows that the bulk of the organic matter of the soil is biologically inert. Lignin, a complex molecule which is present in large quantity in many plants (wheat straw, for example, is 40 per cent lignin), is only slowly attacked and can therefore accumulate while cellulose and starch are oxidized away. Lignin seems to form a still more stable compound with the more resistant proteins, giving a *lignoprotein* of indefinite formula. This lignoprotein, like clay, is an insoluble colloidal acid which can react with bases and so can be useful in holding elements like calcium and potassium in an insoluble but available form. These lignin complexes comprise most of the organic matter. The organic colloids have smaller particles than clay; those of sodium and ammonium are highly dispersed and pass through a porous-pot filter. Some of this material may be isolated by washing a soil with dilute acid (to remove calcium, which prevents dispersion of the colloid), and then extracting with ammonia solution.<sup>2</sup> The extract is very dark brown. Some workers have tried to measure the content of organic matter in soil by the depth of this colour, but this is not very sensible since the colour is just a pigment produced by some bacteria as a by-product, and need not be closely related to the organic content. The colour is like that seen in streams from peaty country.

<sup>2</sup> This extraction is commonly done with 2N ammonia at room temperatures, but is much more thorough if done in a closed bottle which is immersed in a boiling waterbath for some hours.



Stable manure if well rotted also resembles the organic matter of soil—that is, most of it consists of colloidal lignin complexes. Manure is also valuable for its inorganic constituents and for its stock of available nitrogen; these are dealt with elsewhere.

### “Humus”

The common term for the organic matter of the soil is “humus”. This term, in spite of its compactness, has been avoided here, since it has such vague, almost mystical, associations. The idea that plants feed on humus prevailed into the nineteenth century, and it still lingers on, in spite of the success with which plants are grown in solutions of simple salts. Residues of plants are said to be humified when they lose their structure and identity in the soil, and one constantly meets the view that this “humification” is a good thing. There is some confusion here. It is good that coarse leaves and stems should be broken down physically; their potassium and calcium cannot be used again until they are attached to units of colloidal size. It is also essential for fresh residues high in carbohydrate to be decomposed before a crop is put in (see p. 144). But if we define humification as the conversion of miscellaneous active and inactive material into the inert lignoprotein which constitutes the bulk of humus, this may be good physically but it is difficult to see how it could be good chemically.

### PHYSICAL EFFECTS OF ORGANIC MATTER

Organic matter has the reputation of improving the physical properties of both sandy and clayey soils.

(a) The main effect on sandy soils is to increase their power to hold water—best measured as the field capacity. Organic matter commonly has three times the water-holding power of the same weight of clay. This effect is not achieved with *added* organic matter, since even 100 tons per acre could hardly retain half an inch of rain for use by plants. It is doubtful whether a ton or two per acre does more physically than help to hold soil against the wind.

(b) The effect on clayey soils concerns not water-holding power but structure. Firstly, if organic matter is present in large amounts its properties predominate over even a heavy clay. Thus, at Kooweerup a soil with 20 per cent organic matter and 50 per cent clay feels and looks not clayey but peaty. It does not form clods, is easily worked in wet weather, and is loose and even powdery when dry. Organic matter between 10 per cent and 20 per cent still prevents the structure from being really bad. Below 10 per cent, structure may become worse as organic matter decreases in quantity, but its quality now becomes very important. The organic matter formed in the presence of good supplies of calcium is often associated with good structure—for example, the chernozem-like types of the Wimmera. Leached soils in southern Victoria which contain



as much as 7 per cent organic matter still have a poor structure. The bacteria which predominate in the better soil may be different, or possibly they produce different by-products, such as mucus, which help to hold the aggregates together.

This discussion refers to the physical effects of the largely colloidal matter into which plant and microbial residues are converted. The more massive residues of plants can also help in preserving soil structure by protecting the surface from the beating of rain.

#### TOTAL AMOUNT

##### (a) *Estimation*

The total organic matter in soil has been estimated in the past from the loss of weight noted after heating the sample to red heat. This is fallacious. The organic matter is certainly destroyed by the heat, but large quantities of combined water are also lost from the clay and silt. Thus a non-calcareous clayey soil from a flat in the Mallee lost 7 per cent of its weight on ignition, but other analyses showed that it contained less than 1 per cent of organic matter. "Loss on ignition" is hardly ever worth knowing, unless a soil is really peaty, when it is not a bad figure for organic matter.

The method most in favour today is to measure the total carbon in the soil (by catching and weighing the carbon dioxide that is formed on strong heating) and to assume that this carbon makes up 58 per cent of the organic matter—which is generally close to the true figure. Any  $\text{CaCO}_3$  is first destroyed by dilute sulphurous acid, since it would otherwise also give  $\text{CO}_2$  on heating. One drawback to this method is that so many Australian soils contain charcoal formed from the burning of trees. This charcoal is included in the analysis; but since it is massive and inert, it should not be confused with the true organic matter, which is mostly colloidal and in which carbon is chemically combined. A quicker and easier method which avoids this last difficulty is to measure the amount of a standard oxidizing agent, such as chromic acid, which is consumed in destroying the organic matter of a weighed sample of soil. Again an arbitrary figure is used to convert this value into "total organic matter", (see p. 201).

A still more conventional figure may be reached by determining the percentage of nitrogen and multiplying this by 20. The proportion of 5 per cent of nitrogen is a fair average for the organic matter of surface soils, but it is far from constant. Many subsoils contain more nitrogen than this in their organic matter. The reason for the large number of analyses recorded for total nitrogen is that the figure was thought to have a bearing on the need of a soil for a nitrogenous fertilizer. We know now that this is not so; probably the main use of knowing the total nitrogen is to calculate the C/N ratio, as will be seen later.



(b) Representative Soils

The total organic matter present in representative soils is collected in Table 22. This shows that soils in wetter and cooler climates contain more organic matter—for instance, the poor, light grey Hallam loam from the Central District (no. 2) ranks higher than the darker, more fertile soil of the

TABLE 22  
TOTAL ORGANIC MATTER IN SURFACE SOILS IN VICTORIA

District	Climate			Texture	Total O.M. per cent	Remarks
	Rain- fall inch	Length growing season months	Annual Temp. Deg. F.			
1. E. Central ..	30	11	58	Sand	2.2	Podzolic
2. E. Central ..				Loam	5.8	Podzolic
3. E. Central ..				Friable clay loam	8.0	Red or black on deeply weather- ed basalt
4. Near Western	23	10	57	Loam	2.1	Normal podzolic
5. Near Western				Loam	10.5	Immature tuff
6. Wimmera ..	18	7	59	Clay	2.6	Chernozem-like, calcareous
7. Northern ..	17	7	60	Loam	2.0	Red-brown earth
8. Mallee ..	11	5	62	Sand	0.6	Alkaline, calcareous
9. Mallee ..				Loam	1.3	Alkaline, calcareous

All these are mean figures taken from 6 to 12 samples.

Wimmera (no. 6). The reason appears to be as follows. The organic matter is being constantly replenished from atmospheric CO<sub>2</sub> by plants and autotrophic bacteria and constantly decomposed by other micro-organisms and the respiration of plants to give carbon dioxide. Its total amount therefore depends on the relation between these two effects<sup>3</sup>. Under a high rainfall and with a long

<sup>3</sup> If *S* is the total amount of organic matter present per acre and *r* is the fraction annually oxidized, then the amount so destroyed each year is *S.r*. Now an undisturbed soil keeps its organic content at a steady value. So the annual addition per acre in roots, etc., *A*, must equal the annual loss, *S.r*. That is, *S*=*A*/*r*. In the wet tropics both *A* and *r* are much greater than in temperate climates, but *S* has a moderate value. Incidentally, the statement found in many textbooks that “organic matter in the tropics decomposes more rapidly than it is formed” has no meaning.



season plants make more growth and bacteria do not seem to become correspondingly more active. Bacteria are more depressed by low temperatures than plants, so cooler climates have more organic matter. Soils which have lain under swampy conditions form a special case. Bacterial decomposition in swamps has to go on with only small amounts of oxygen, and is therefore relatively slow, and since the growth of plants is just as rapid as on well-drained land, swampy soils are high in organic matter.

Naturally there are plenty of differences between soils in the same climatic zone. Thus, sandy soils are relatively dry and so are low in organic matter for their district. Clayey soils have a wetter climate of their own, so are relatively high. Poverty in phosphorus also limits the growth of plants, but does not cut down the rate of microbial attack to the same degree; this may explain the great difference between soils 4 and 5, which occur on the same property, the latter being chemically rich, on the slopes of a volcanic cone. A series of virgin surface sands from the Ninety Mile Desert of South Australia show the same effect, ranging from .03 per cent N, .002 per cent P to .15 per cent N, .011 per cent P. Lastly, the use of the land is important. Grassland soils are higher in organic matter than cultivated soils—partly because of the great production of roots by some grasses, partly because of the periods during which cultivated land is bare and so receives no addition in roots of any kind. The effect is most clearly marked in regions of bare fallowing, where organic matter becomes severely depleted and the soil in consequence loses its structure. The very high organic content of the chernozems (p. 28) is a puzzle, but is probably related to the huge mass of very fine roots produced by the perennial grasses.

This discussion relates almost entirely to the surface eight inches or so. In the deeper layers there is much less organic matter (Fig. 31) and little is known about its properties. The peculiar maximum in the subsoil of the sandy podzol represents the "coffee-rock" (p. 19).

#### ANIMAL MANURES

The use of animal manures on the land is of very little importance in Australia, mainly because animals graze in the open all the year, but also partly because the horse population has decreased with the use of machinery. Manure is used only on the most intensive small holdings, either for flowers or vegetables.

The solid manure of most animals is a general fertilizer, containing useful concentrations of many elements that were present in the food—not only the major elements calcium and phosphorus, but minor elements, such as manganese and zinc, as well. It may also be a useful source of nitrogen, depending on the species of animal and its food. The bulky manure of a herbivorous animal (such as the horse) helps the physical properties of the soil as well.



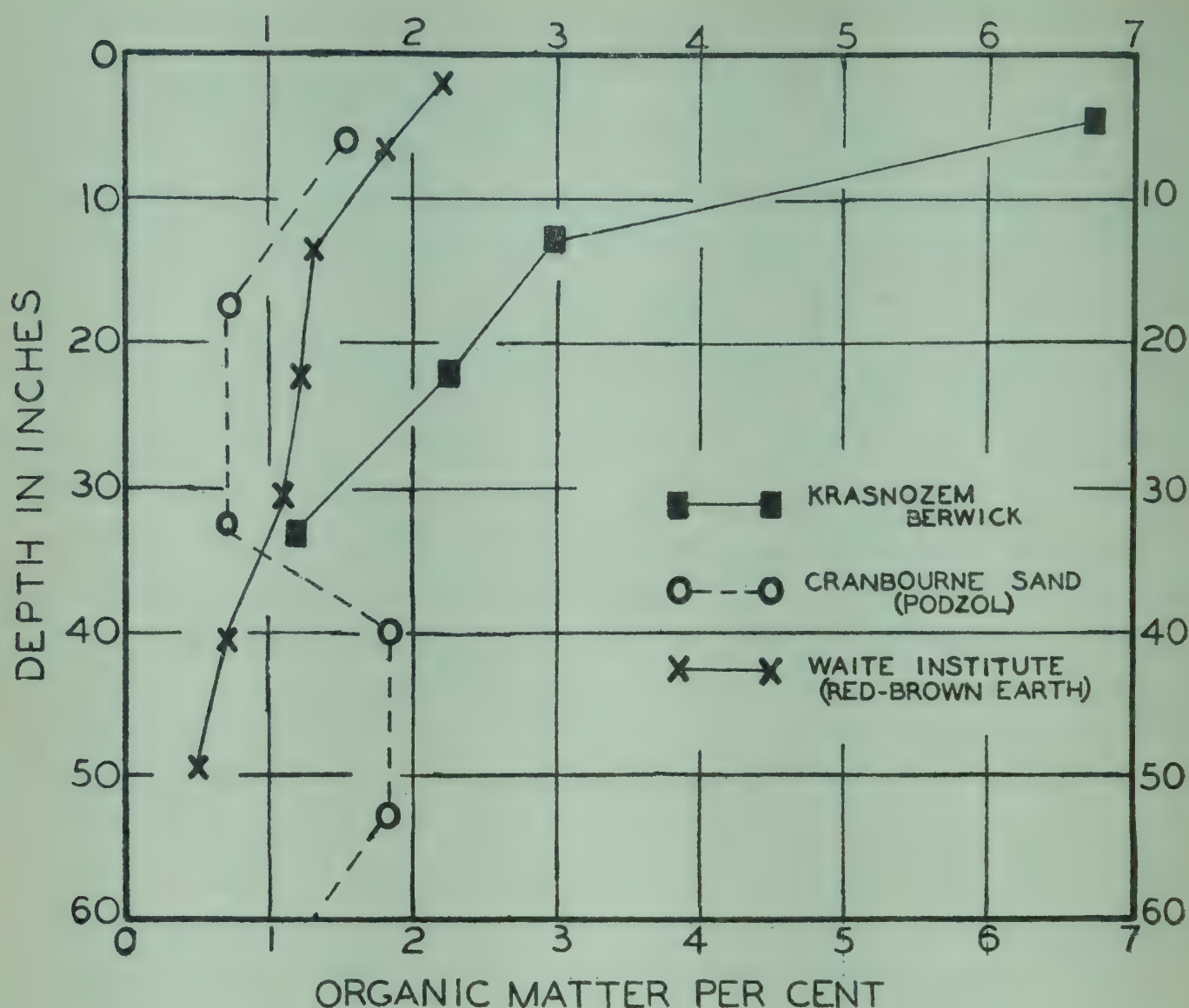


Fig. 31. Amount of organic matter in soil profiles.

On dairying or other grazing land the grazing animal constantly returns to the soil the bulk of the elements in its food, except for carbon, which is oxidized to provide warmth and energy. The dairy-farmer periodically spreads the manure fairly uniformly over the land by pasture harrows. The urine contains organic nitrogen compounds which rapidly produce ammonia; the nitrate ultimately formed may show its effect in a crop of oats grown on that land the next season, with green and tall plants among paler green population: such "fertility spots" show that the nitrate production of the soil is otherwise poor. On a well-run dairy-farm the washings from the milking-shed, containing the nitrogen and potassium of the urine in high dilution, are collected in a tank and applied to the paddocks.

#### COMPOST

Compost is the name given to the product of microbial attack on various organic wastes under controlled conditions. A mass of material such as grass clippings, weeds and prunings of trees, is treated with a nitrogen fertilizer, moistened and compacted, sometimes packed with alternate layers of soil, and



left to ferment for some weeks. Bacteria and fungi, thus provided with their necessary nitrogen, oxidize the cellulose and turn the waste into a dark structureless mass in which the nitrogen is present as protein and the main constituent is colloidal like the ligno-protein of soil. In the process the temperature rises to  $50^{\circ}\text{C}$  and the seeds of most weeds are destroyed. The resulting compost has the physical virtues of soil organic matter, and chemically it has a moderate status in nitrogen and contains a useful amount of other nutrient elements, particularly potassium, which were originally collected from the soil by the plants used for the compost and which are thus restored to the land.

These organic manures being all-round fertilizers often bring about excellent results; so much so that some people have suggested that organic forms of nutrients are better than inorganic. There is no foundation for this doctrine. It is just conceivable that plants may absorb some organic molecules with vitamin-like properties, which are present in the bacterial products of animal manure but not in the rest of the soil. It is conceivable, but has never been proved and is in any case improbable. Plants grown in nutrient solution are as prolific and as rich in vitamins as any grown in soil, however rich it may be in fresh organic matter.



## CHAPTER XII

### THE NITROGEN CYCLE

THE NITROGEN CYCLE IS THE MOST IMPORTANT OF ALL THE CYCLES OF ELEMENTS through the soil and the plant, and has received most attention.

#### FORMATION OF AMMONIUM AND NITRATE

Most of the nitrogen in plants exists in organic combination as proteins. Plants build up this protein, in the same way as other complex molecules, from simple substances. All plants except the Leguminosae (see below) and a few minor groups obtain their nitrogen requirements from ammonium compounds or nitrates; leguminous plants, when living with the proper strain of nodule bacteria, can obtain some or all of their requirements from the gaseous nitrogen circulating through the soil. When the plant or its leaves die, this protein becomes available as a source of energy for micro-organisms; and the final result of their attack is ammonia. This process of *ammonification* is rapid in warm soils, and occurs slowly even at 40°F.; though it is typical of soils that are moist rather than wet, it is not prevented by poor aeration. Except in strongly alkaline soils, the ammonia does not normally appear in the soil in the free state, but as ammonium ion ( $\text{NH}_4^+$ ), which is attached to the colloidal material in a way analogous to potassium, and which exists in only very small amounts (less than one part per million) in the soil solution.

Nitrification by autotrophic bacteria follows if aeration is good, with nitrate the final stage. Intermediate products in this reaction, such as nitrite, rarely occur in important amounts in soil.

Both ammonium and nitrate ions are used by plants and by micro-organisms for rebuilding protein. There is thus the possibility of a closed cycle from plant to plant by way of ammonia, or of ammonia and nitrate, or of microbial protein followed by ammonia or nitrate (see Fig. 32).

#### NITROGEN CYCLE WITHIN SOIL

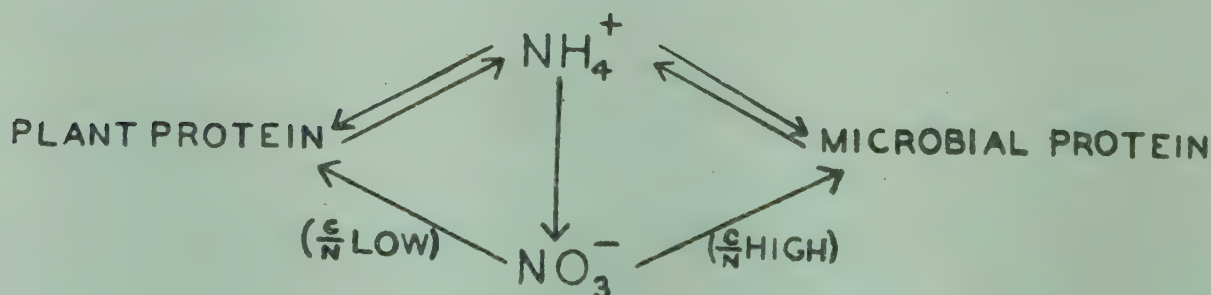


Fig. 32. Transformations of nitrogen in soil.



*Relative Importance of Ammonium and Nitrate*

The doctrine which long held the field was that non-leguminous plants absorb nitrogen only as nitrate ion, and that such fertilizers as ammonium sulphate must be nitrified before they can be used by plants. This doctrine has been disproved, both by tests with culture solutions (which show that some young plants given ammonium nitrate take up ammonium in preference to nitrate) and by observations in the field. A rapidly growing pasture, for example, has been observed to absorb the nitrogen in applied ammonium sulphate in three days—long before it could have been nitrified. On the other hand, nitrate is not adsorbed by the soil but exists entirely in solution, while ammonium is adsorbed; but this need not prove that nitrate is more available than ammonium in soils, since we know today that adsorbed ions are easily taken up by roots. It is unfortunate that figures for ammonium in soils are relatively few.

*Tests of Nitrifying Power*

The best information about a soil's production of nitrate is gained by sampling in the field at monthly intervals, especially in the autumn. We may also test in the laboratory for its "nitrifying power" by incubating it in a moist state at a moderate temperature (say 22°C.) and analysing it after two or three weeks for its nitrate content. This test may be done on the untreated soil, or on soil to which a small amount of ammonium sulphate or of blood (an easily attacked protein) has been added. The purpose of these tests has not always been clear to the agricultural scientists concerned. The first test—the ability of the soil to nitrify its own protein—is the most valuable of the three; it measures simultaneously the quality of the soil's organic matter—which may depend on its recent treatment—and the efficiency of the ammonifying and nitrifying organisms. The ability of a soil to produce ammonia and then nitrate from blood, or to produce nitrate from ammonium sulphate, is not of great interest. All except the most acidic soils can nitrify rapidly if only the temperature and moisture are correct.

*Nitrification as an Acidifying Process*

The transformation of ammonia into nitric acid, as just described, must acidify the soil. One may ask how it is that all soils do not become continually more acidic, since the end-products of microbial metabolism are organic acids, carbonic acid, and nitric acid—to which sulphuric acid must be added (see p. 132). In fact soils do not become acidic unless the bases calcium bicarbonate and magnesium bicarbonate are washed out in the drainage. There are two reasons for this. In the first place, the above statement is incomplete; certainly, free



organic acids are formed, but their calcium or magnesium salts are formed at the same time, and such salts tend to make the environment alkaline. Secondly, plants themselves modify the acidity of their environment. For example, the absorption of biphosphate ( $\text{H}_2\text{PO}_4^-$ ) leaves the solution less acidic; plenty of reactions *within* the plant go in an alkaline direction. Ammonium sulphate, however, undoubtedly acidifies the soil; in long-term experiments on the sandy soil of Woburn in England, plots continuously treated with normal amounts of ammonium sulphate eventually became so acid that the barley crop grown on them was a complete failure. Orange trees on irrigated sandy soils in Victoria and New South Wales have also suffered from acidity which has been brought to a pH below 5 through heavy applications of ammonium sulphate.

#### CARBON-NITROGEN RATIO AND LEVEL OF AVAILABLE NITROGEN

The production of available nitrogen in the soil depends on the composition of the organic matter which is being attacked by micro-organisms. The heterotrophic micro-organisms of the soil obtain the energy needed for growth and maintenance by oxidizing suitable compounds in their environment. If a readily attacked protein (such as blood) is accessible, they use its oxidation as a source of energy; this process sets ammonia free. To take the simple amino-acetic acid (glycine) as representing this oxidation, we have—

$2\text{C}_2\text{H}_5\text{NO}_2 + 3\text{O}_2 \rightarrow 2\text{NH}_3 + 4\text{CO}_2 + 2\text{H}_2\text{O} + 210,000 \text{ calories per } 150 \text{ gm. glycine.}$

On the other hand, if a carbohydrate (such as cellulose or starch) is plentiful, this will be attacked, giving organic acids as intermediate products, and eventually carbon dioxide—

$\text{C}_6\text{H}_{10}\text{O}_5 + 6\text{O}_2 \rightarrow 6\text{CO}_2 + 5\text{H}_2\text{O} + 680,000 \text{ calories per } 162 \text{ gm. starch.}$

In the former case, more ammonia is produced than the micro-organisms need for building their own proteins; thus ample ammonium, and therefore also nitrate, is available for the growth of plants. In the latter case, the micro-organisms multiply and so use more of the reserves of ammonium and nitrate, and the plants may suffer by competition. Thus we expect a low level of available nitrogen after plant residues high in carbohydrate have been added to the soil, and we cannot expect any improvement until this carbohydrate has been oxidized, and eventually the locked-up nitrogen is turned back into ammonium and nitrate by the decomposition of microbial cells.

Table 23, taken from the work of Parbery and Swaby in Sydney, illustrates the action of “green manure”—that is, fresh plant material dug into the soil—in determining the nitrogen nutrition of the succeeding crop. Such material is much more quickly attacked than the bulk of the organic matter of the soil. Green manure of high quality—for example, field peas at flowering-time—



may quickly liberate enough nitrate to meet the crop's needs. Carbohydrate material, however, such as straw, decreases the nitrate below that which the untreated soil would have produced, so is harmful unless accompanied by a nitrogenous fertilizer. The yields quoted are those of rye grass grown in pots containing a sandy soil mixed with the green manure and given additions of all the necessary nutrients except nitrogen, so that the quality of the green manure

TABLE 23  
QUALITY OF GREEN MANURE  
AND ITS EFFECT ON GROWTH OF RYEGRASS  
(PARBERY AND SWABY, *Ag. Gaz.*, N.S.W., 53, 357)

	$\frac{C}{N}$	Dry weight of grass after 3 months, gram
Beans haulms .. .. .	24	8.2
Beans, whole .. .. .	12	15.8
Field peas, flowering .. .. .	12	18.9
Oat tops .. .. .	22	10.3
Millet, mature (straw) .. .. .	93	—
"Fat hen" .. .. .	12	18.9
Blood .. .. .	4	23.3
Eucalypt mould .. .. .	51	4.1
Control .. .. .	—	10.0

determined growth. All pots received equal amounts of nitrogen in the green manure. The plants on the control pots produced 10 gm. of dry weight; the rich protein blood and the leguminous crops (peas and beans) caused a great increase in weight, as also did the non-leguminous weed "fat hen", which must have grown on soil high in nitrate to be so nitrogenous itself. When the pods were removed from the beans, however, the residues (haulms) were of low quality and depressed the yield. The leaf-mould also caused a great decrease, while the plants grown after adding millet straw were too poor to harvest. A young crop such as oats used as green manure is also much better than a mature one. All of these results fit in well with the C/N ratio of the manure. One might draw the line at a value of 20—anything with a ratio above this is a poor material for nitrification. Analyses of the rye-grass plants harvested after eight months showed that all those growing on the four low-ratio manures had recovered at least 40 per cent of the added nitrogen, while none of the others reached 20 per cent.



## CARBON-NITROGEN RATIO OF SOIL

If we adopt the conventional figures that carbon makes up 58 per cent of organic matter and nitrogen 5 per cent, the ratio of carbon to nitrogen<sup>1</sup> in the soil is 11.6; in fact this ratio lies between 10 and 13 for most soils. However, this is not necessarily a favourable value as it would be for a green manure, since much of the nitrogen is present as resistant compounds, and the ratio of *attackable* carbon to *attackable* nitrogen really determines the ability of the soil to keep up its supply of nitrate during the next few weeks or months.

The C/N ratio of the soil varies among the different groups, being greatest in the highmoor peats, which are high in cellulose and low in protein and so particularly poor in available nitrogen (C/N=50). The relatively stable figure of normal soils is due to the balance of various factors. If the ratio is increased (by adding carbohydrate to the soil), microbial oxidation of carbon compounds is increased and simultaneously nitrate and ammonium are locked up in microbial cells, and less nitrogen passes into these more active compounds which are liable to be lost from the soil; further, the soil becomes less favourable for the growth of plants which rely on ammonium and nitrate, so again less carbon is added to the soil. All this tends to bring the ratio down again. If the ratio is decreased by adding protein to the soil, the consequent rich supply of ammonium and nitrate stimulates the fixation of carbon by plants, nitrogen-fixing plants are depressed by competition, and nitrogen may be lost, for example by the leaching of nitrate. As before, the ratio tends to return to its steady value.

## BALANCE SHEETS FOR NITROGEN: ENTRY AND EXIT

Analyses of drainage waters show that nitrate is constantly being lost from the soil. At Rothamsted in England, for example, with a humid climate and an annual rainfall of 26 inches, a total amount of 1,200 pounds of nitrogen was washed into the drains (at five feet depth) during 47 years. This soil was kept bare; the annual loss from cropped soil is much less. Besides this loss to rivers and underground storage, fixed nitrogen may also be lost as nitrogen gas. The extent of this loss in normal soils is unknown, but it is probably not great. The term *denitrification* is used for this biological conversion of nitrate into nitrogen. Soils as alkaline as pH 8 may also lose nitrogen in the form of ammonia. As yet little is known of the importance of this effect.

To balance these losses, more nitrogen must enter into the cycle from the atmosphere, especially if crops or livestock are being removed from the land (see Fig. 33). A little fixed nitrogen—both as ammonia and as nitric acid—

<sup>1</sup> C/N ratios are quoted here in the usual way as the relative weights of the elements. It would perhaps be better to calculate the atomic ratios, but this is rarely done. Thus if the relative *weights* are 12:1, the *atomic* ratio is 12/12 : 1/14, i.e. 14:1.



comes in with the rain. The amount of this in Australia is not known. It may be of the order of five pounds per acre per annum in the temperate parts, and more on the sub-tropical and tropical east coast, where summer thunderstorms are common; fifty pounds per acre has been quoted in equatorial regions. Ammonia in gaseous form in the atmosphere can also be directly taken up as ammonium ion by soil colloids. Such additions of fixed nitrogen, however, cannot compensate for losses by drainage, denitrification, and sale off the farm. We come then to consider microbial fixation of the gaseous nitrogen circulating through the soil and making up four-fifths of the soil air.

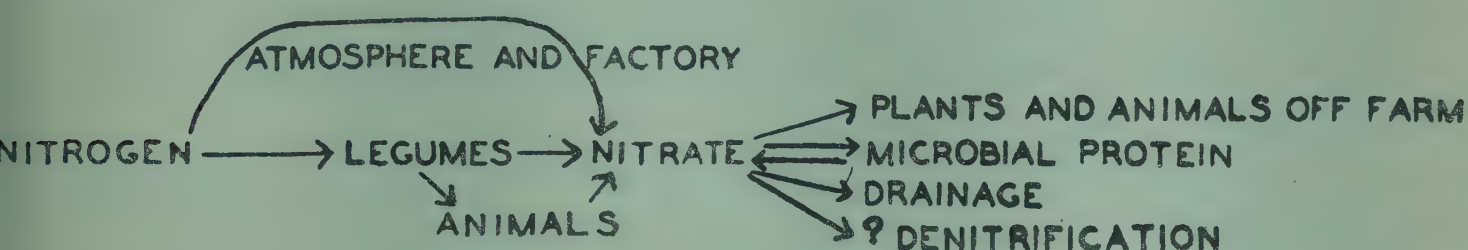


Fig. 33. Income and export of nitrogen.

### *Symbiotic Fixation of Nitrogen*

Plants of the family Leguminosae ("legumes") characteristically carry root nodules in which the bacterium *Rhizobium* is linked with the plant cells. These bacteria convert gaseous nitrogen into organic nitrogenous compounds almost all of which may be used by the host plant. While the nature of this fixation is still under discussion, it probably leads to aspartic acid<sup>2</sup>, which the rhizobia produce more rapidly than they need. Clovers and medicks (the latter especially in drier districts) are the most important nitrogen-fixers in temperate Australia. Native legumes are widespread in the bush—the Acacias in particular. *Casuarina* trees, which are not legumes, also add nitrogen through a microbial association. The term *symbiotic* includes all such associations.

If we suppose that the income from atmospheric ammonia and nitric acid equals the loss in drainage at about five pounds per acre each, and that the soil is not being eroded, then we can calculate balance sheets as follows for wheat-growing and dairying. The order of the loss is (a) about 19 pounds an acre annually on a wheat farm, where a 25-bushel crop is sold off the same land every second year, and (b) about 18 pounds on a dairy farm, where one cow is carried to two acres and the milk is sold. These losses can easily be balanced by leguminous crops or pasture plants. A good crop of clover might fix 50 pounds of nitrogen, and if this were grazed off about 25 pounds would eventually be added in a year. This calculation is necessarily rough, being designed to show the order of the figures concerned. Many overseas workers have shown the increase in total nitrogen when soil is left under pasture.

<sup>2</sup> COOH.CH(NH<sub>2</sub>).CH<sub>2</sub>.COOH



*Non-symbiotic Fixation of Nitrogen*

A great deal of work has been done in other parts of the world on free-living bacteria which can use gaseous nitrogen for building their own protein. There are two groups of these—viz. *Azotobacter*, an aerobic organism of which several species have been described, and *Clostridium butyricum*, an anaerobic organism. Neither of these organisms appears to be of the slightest practical importance in affecting the nitrogen status of Australian soils; *Azotobacter* seldom occurs naturally in this country. In fact, in spite of colossal labours devoted to the study of *Azotobacter* in many countries, there is little evidence that it has an important influence in keeping up the total nitrogen in any part of the world. It certainly never produces nitrate from gaseous nitrogen, as is often stated.

Other forms of life in the soil may turn out to be important—in particular, some of the blue-green algae, which are known to fix nitrogen. For the present, however, it appears that only the legumes can be counted on for restoring the normal losses from the land.

## NITRATE AND CEREAL CULTURE

The fluctuations of available forms of nitrogen in the soil are of great practical interest. Most of the work on this subject deals with nitrate and not with ammonium; whatever may be the significance of ammonium, the emphasis on nitrate is justified for many crops by the success with which the figures for nitrate can be applied in practice. Chemical analysis for nitrate is fairly simple, and results are reliable provided that a large enough number of replicate samples are analysed to allow for the erratic distribution of nitrate in soil. Owing to the economic importance of wheat, most of our information on this subject has been collected from studies of rotations in which wheat is grown after bare fallow. This will first be discussed.

The wheat belt of southern Australia has a hot dry summer and a cool winter during which enough rain falls to moisten the land to a depth of two feet or more. The seed is sown when the first moderate rain falls in the autumn or early winter, on land that has been fallowed and kept bare of weeds for about ten months. At this stage the soil has a high reserve of nitrate. Thus, in a study at Rutherglen the nitrate stored in the top foot alone in May of one year was equal to 135 pounds of nitrogen per acre; at the Waite Institute in Adelaide the amount stored in the top three feet averaged 80 pounds over five years. Allowing one-and-a-half pounds of nitrogen as necessary to produce one bushel (60 pounds) of wheat, the lower figure was enough to provide for 54 bushels of grain, even if no more was produced during the actual cropping season. If we



study only the uppermost 6-8 inches, where the nitrate is much the most concentrated, again the storage is high, with a common value of 30 parts per million or about 60 pounds per acre. It is not surprising that crops sown on fallow in the wheat belt give no extra growth when treated with nitrogenous fertilizers. As the season advances, the nitrate is depleted, some going into the crop and some being washed to the deeper subsoil. By the end of September, when the crop has made its maximum vegetative growth, the figure has fallen very low (see Table 24). The crop makes no more demand on the nitrate, but

TABLE 24  
NITRATE NITROGEN IN TOP FOOT,  
UNDER WHEAT AND CLEAN CULTIVATED,  
RUTHERGLEN, 1930-1 (*J. Ag. Dep. Vic.*, 1932)

	15 May	28 July	18 Aug.	8 Sep.	10 Nov.	8 Jan.
Cropped soil, parts per million ..	28	11	5	2.0	1.8	2.5
Bare soil, parts per million ..	28	17	12	8	—	31
N in crop, lb. ..	0	36	70	102	122	—

the figure remains low until the death of the crop, and for some weeks after.

Suppose that the next year is one of bare fallow. Nitrate accumulates during the autumn, when both temperature and moisture are favourable, but it does not reach the high level of twelve months earlier. During the winter the rain removes some reserves while the cold suppresses any fresh formation. Only in the succeeding spring (again with warmth and moisture) does nitrate rise to a high level, which it now retains during the dry summer to start the cycle again with the new crop in the autumn (Fig. 34).

The rapid formation of nitrate on the fallow in spring contrasts with the low values found under the crop. In both cases the soil is warm and periodically moist; the difference must lie mainly in the quality of the raw material which the micro-organisms have at their disposal. We do not know the nature of this unfavourable material associated with the last months of the crop's life, but until this has gone (commonly in the succeeding winter) nitrate does not accumulate rapidly. The effect of fallowing, then, apart from the opportunity of cleaning weeds, is firstly to create a favourably low ratio of attackable carbon to nitrogen; secondly, to allow nitrate to accumulate by preventing the growth of weeds which would otherwise assimilate it. Possibly cultivation may also help by bringing bacterial colonies into contact with nitrogenous material, but this is doubtful.



## NITRATE IN SOIL; CROP-FALLOW ROTATION

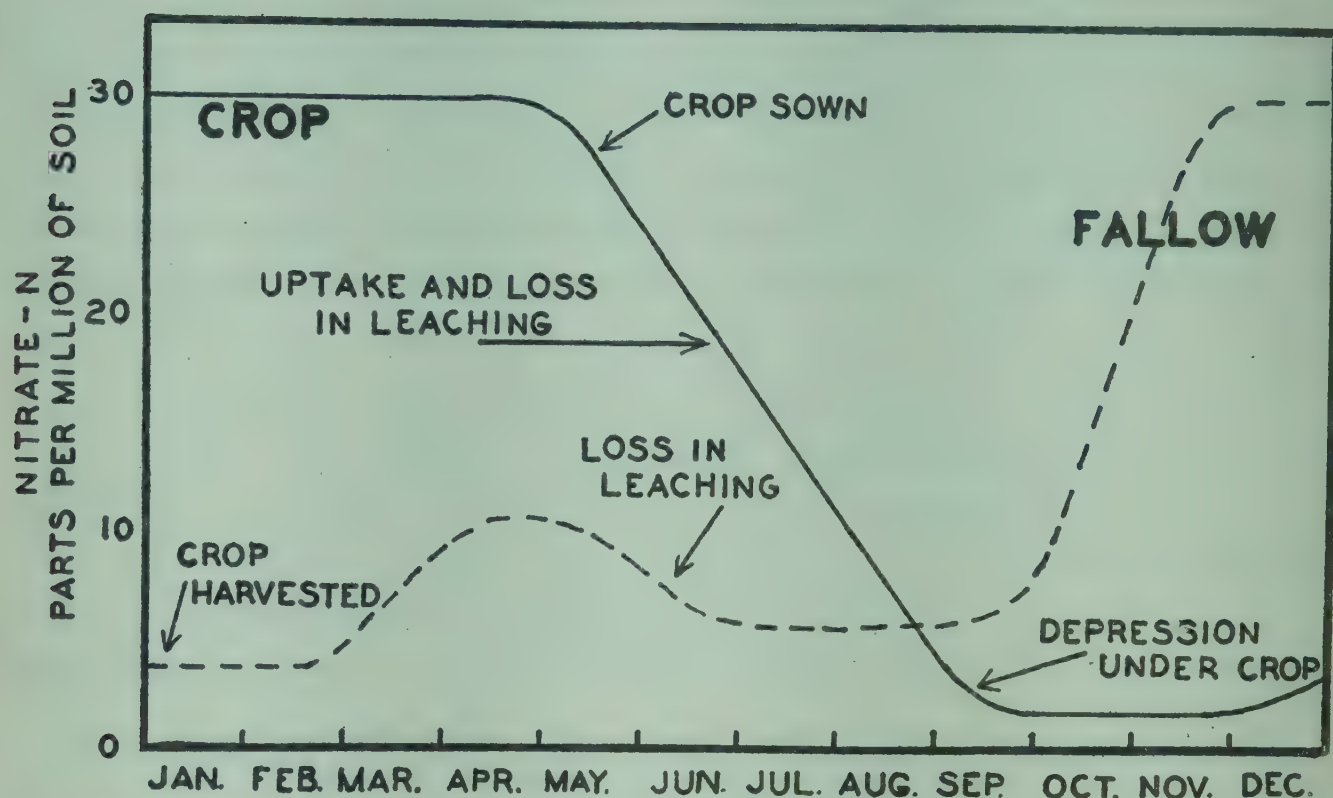


Fig. 34. Nitrate nitrogen in surface soil in northern Victoria. Continuous line, crop year: broken line, fallow year.

## NITROGEN IN WETTER CLIMATES

## (a) On Crops

The problem of nitrogen in the wheat belt is relatively simple; nitrates are accumulated each spring under fallow and are still there when the seed is sown in autumn. But new problems arise as soon as the rain is heavy enough to wash nitrate into the deep subsoil. This happens in England and in the wetter coastal parts of Australia. Oats and barley are grown in these parts rather than wheat, but nitrogen nutrition presents similar problems for all these crops, as well as for others such as flax and potatoes. We may first consider the intermediate case of the dry belt in southern Victoria lying near Werribee. The soil is a red-brown earth (p. 27). The rainfall here averages 19 inches annually, and while the district is essentially oatgrowing, the dry climate led to the establishment of the State Research Farm at Werribee, where wheat-breeding has been a major activity. Wheat is sown here after a year of fallow, as in the normal wheat belt. In a wet autumn, however, the rain washes out some nitrate from the fallowed land, and probably causes denitrification in the waterlogged soil; for example in 1935 after five inches had fallen in April only two to three parts per million of nitrate nitrogen remained in the top six inches. If such weather occurs, a long period of fallow is useless, except for the opportunity of destroying weeds, and nitrogenous fertilizers increase the crop on fallow land.



In wetter climates than Werribee, this is the common situation; crops succeed pasture or other crops and some other method than fallow must be sought for supplying the crop with its necessary nitrogen. In fact this problem is general for oats, which are seldom sown on fallow.

The most obvious method is to apply a nitrogenous fertilizer—in normal times, ammonium sulphate. Whether applied in autumn or spring, this has often greatly increased the yield of both straw and grain of oats sown after another cereal (wheat or oats). For example, at the Waite Institute near Adelaide, with 16 inches of rain from May to October, a hundredweight of ammonium sulphate increased the grain by an average of 12 bushels over seven years; at Rutherglen, with 13 inches in the same period, it increased the total crop from 26 to 41 cwt. In the wheat belt away from the wetter fringe, the effect is slight or nothing.

Two tests may be tried to determine whether additional nitrogen is needed. If the soil contains as much as 10 parts per million of nitrate nitrogen in the top six inches at the time of sowing, additional nitrogen is probably not needed. There remain, however, many doubtful cases. The wetter the winter, the more likely it is that more nitrogen is needed. A further test has been devised for testing the crop itself in early spring. If the nitrate in the soil is ample, a cereal crop contains a reserve of nitrate in its sap; if nitrate in the soil is low, then all that the crop takes up is quickly assimilated—that is, reduced to amino-acid or protein. A thin disc of the stalk is tested with a solution of diphenylamine in sulphuric acid; a deep blue colour shows that nitrate is ample, and a negative test indicates that a nitrogen fertilizer should be added. This test should only be positive in early spring (August). By late October healthy plants react negative.

If the crop is sown on land that was carrying a good clover pasture, it is unlikely to need any additional nitrogen. Crops grow better when the soil slowly and steadily produces its own supply of ionic nitrogen through the season than when all the supply is added at once as soluble fertilizer. The experiments at the State Farm at Rutherglen (Table 25) illustrate some of the above principles, but the continuously cropped wheat is limited by other factors besides nitrogen. Similar arguments apply to other crops—for example, potatoes, for which nitrogenous fertilizer is often given.

#### (b) *In Pastures*

Clovers are an essential feature of a good pasture; we might therefore expect that the grasses in such a pasture would have ample ionic nitrogen. Nitrogen fertilizers have increased the growth of grasses in early spring in southern Victoria, but the increase is not great and may be followed by a



decrease in late spring. In England ammonium sulphate seems to be valuable during a cold spring when the days are already long but temperatures are below 50°F.—that is, when bacterial production of nitrate is very slow. The growth of a pasture, of course, is a very different matter from that of a crop, since so much of the nitrogen of the herbage is continually grazed and returned to the soil in urine in a rapidly nitrified form. Analyses for ionic nitrogen under pasture show that both nitrate and ammonium are kept down to the order of 1 to 5 parts per million.

TABLE 25  
GROWTH OF WHEAT IN VARIOUS ROTATIONS (RUTHERGLEN, 1937)  
(J. Ag. Dep. Vic. 1940, 205)  
*Bushels per acre with various fertilizers*

	Nil	Super 1 cwt.	Super 1 cwt. $\text{Am}_2\text{SO}_4$ 1 cwt.	Nitrate N at sowing, surface soil  parts per million
Wheat after sub. clover ..	26	37	36	22.5
Wheat on fallow ..	14	29	34	13.2
Wheat after wheat ..	10	14	14	5.0

#### LEY FARMING AND ROTATIONS

This is a convenient point at which to deal with the principles of “rotation”—that is, alternating the crops on the same land. It has long been known that if land is used continually for any one crop its yields decline. One reason is biological; fungus and insect pests become established, and since these commonly specialize on one host plant they may disappear if any new crop is grown. Some weeds also may be got rid of by a change in crop. But in addition to this, any system of cultivation for many years causes the structure of the soil to deteriorate, and the structure is best restored by a period under pasture. Further, the supply of nitrate from the soil’s own nitrogen must fall off if non-leguminous plants are grown continually. These last two points are met, as well as the first, by alternating cereal cropping with a period of three or four years under clover pasture. This kind of rotation is called “ley farming”, a ley being a temporary pasture. A primitive form of this has been established in the drier wheat belt, where land is simply left to be grazed after the crop is taken off, and where the pasture that then occupies the land includes the leguminous medick. (This



leaving land to be colonized by native plants was formerly called "fallowing" in England.) On the wetter margins of the wheat country, as at Rutherglen, ley farming is of a more deliberate kind, subterranean clover being introduced and kept vigorous by "top-dressing",—that is, broadcasting superphosphate at the rate of a hundredweight or more per acre. The land that is broken up from a clover pasture gives here a higher yield of wheat than does land that has been bare-fallowed. One benefit of fallow—conserving water—is not needed where the rainfall is high (22 inches) and the pasture plants die in the spring; the other main benefit—accumulating nitrate—is also not needed where leguminous residues are plentiful.

The traditional doctrine, that rotations are good because different crops allegedly take different nutrients from the soil, has little substance in it apart from the special case of nitrogen. There may be a slight analogy with other nutrients than nitrogen, in that some plants can dig out a nutrient element from a low-grade source and excrete some of this in the last weeks of their life to be a higher-grade source for their successors; but too much should not be made of this.

### *Declining Fertility*

The cereal plots at the Victorian stations of Rutherglen, Longerenong, and Werribee show a steady decline over 30 years in the yield of oat crops grown immediately after wheat in the rotation wheat-oats-fallow. The causes of this decline have not been analysed; the wheat which is grown after a year of fallow does not show it. It is probably partly due to a poorer structure after long cultivation, and partly to a lower level of nutrients, including the trace elements, after long exploitation. Where animals are grazed on the land, whether on an oat crop or on a leguminous pasture, there is no decline in crop yields. Not all cases of decline are associated with a low figure for organic matter. For example the worst decline in fertility on the krasnozems of the Dorrigo tableland (N.S.W.) occurs on soils which have 12 per cent of organic matter, but are low in nutritive elements, including Ca and Mg.

### FORMS OF NITROGENOUS FERTILIZER<sup>3</sup>

Nitrogenous fertilizer can be applied in various ways:—

(1) Ionic compounds—ammonium salts or nitrates. Few comparisons have been made in Australia on the relative merits of these forms, since nitrate is

<sup>3</sup> The terms *fertilizer* and *manure* are a constant source of argument. In this book I have followed American usage, by which *manure* means only organic waste products, and *fertilizer* is the more general term including especially the simple chemical compounds like superphosphate. The English usage is *manure* for the general term, and *minerals* or *artificial* for the simple compounds. Australian usage is intermediate; *manure* often means superphosphate, but *fertilizer* is also used as in America, and fortunately one seldom hears the word *minerals* in this sense.



normally much more expensive per pound of nitrogen (30 per cent higher in 1948).

(2) Materials which decompose in the soil within a few weeks, liberating ammonia. These include calcium cyanamide ( $\text{CaCN}_2$ ), urea ( $\text{CON}_2\text{H}_4$ ) and blood, only the last of which is used in Australia. Blood is a high-grade protein. It is sometimes spoken of as though it were comparable to the bulky organic manures, but it does not add to the organic content of the soil; it merely provides a steady stream of ionic nitrogen, and could conceivably be replaced by a synthetic compound which did the same thing. Other waste products high in protein may be used for the same purpose, for example castor meal—the residue of castor seeds from which the oil has been pressed or extracted; this is slower in its action than blood.

(3) Animal manures, the nitrogen status of which depends on the species and the food. The normal stable manure, produced where cattle or horses have been housed with a straw bedding, is a low-grade source of nitrogen, though it is often used in such heavy amounts as to give a satisfactory supply to plants. It is commonly “rotted” or left open to microbial attack for about three months; during this time the bacteria oxidize the available carbohydrate of the straw, so reducing the C/N ratio, and convert most of the ammonia (from the urea of the urine) into organic nitrogen. Any adsorbed ammonium which remains comprises the immediately useful nitrogen of the manure. The rest of the nitrogen may also contribute to succeeding crops.

With this exception, nitrogenous fertilizers differ from all others in being used entirely for the current crop; they have not even the slight residual value of superphosphate.

Their use in Australia to date has been slight. The ratio of nitrogen to phosphorus used in Australia in 1937 was 1 to 14, as compared with 1.6 to 1 in Holland where agriculture is intensive. The difference in relative importance is simply due to the fact that grass and wheat are the two main crops, and these do not need added nitrogen. Sugar cane is the chief Australian crop on which nitrogen fertilizer is used.



## CHAPTER XIII

### PRIMARY MINERALS IN SOILS

THE PRIMARY MINERALS OF ROCKS WHICH HAVE SURVIVED CHEMICAL WEATHERING are of interest, chiefly since they contain reserves of many essential elements. These are found mostly in the "fine sand" fraction, particularly within the range between  $20\mu$  and  $50\mu$ , and can be identified under the microscope by the ordinary methods of the geologist. In all but the youngest soils, material above  $50\mu$ , especially the "coarse sand" fraction (0.2—2 mm.), contains little besides quartz and concretions of iron oxide. Quartz usually predominates in the finer fractions also; it is chemically inert and of no use to plants, so is merely a diluent. Primary minerals other than quartz do not occur in fractions below  $5\mu$ , since the great surface of such small particles leads to rapid decomposition.

The most important of the other primary minerals are given below:—

(1) *The Feldspars* ( $\text{KAlSi}_3\text{O}_8$ ,  $\text{NaAlSi}_3\text{O}_8$ ,  $\text{CaAl}_2\text{Si}_2\text{O}_8$ )<sup>1</sup>. These are often plentiful, partly because they make up such a large proportion of igneous rocks, but mainly because they decompose more slowly than many other minerals.

(2) *Calcium Magnesium Silicates*, which contain iron and are heavier than the feldspars. These minerals are classed by geologists as "pyroxenes and amphiboles". Two important examples, augite and hornblende, have formulae too complex to be given here. They are related to a simpler mineral  $\text{Ca}_2\text{Mg}_5\text{Si}_8\text{O}_{22}(\text{OH})_2$ ,<sup>1</sup> from which they differ in containing also iron and aluminium, together with small amounts of minor elements, such as Cu, Zn, Co, and Mn.

Olivine ( $\text{Mg}_2\text{SiO}_4$  with some Fe replacing Mg) can conveniently be put in this group.

These are very valuable silicates which in warm and wet climates decompose quickly and are therefore present in important amounts only in young, rich soils.

(3) *The micas*, namely muscovite  $\text{KAl}_3\text{Si}_3\text{O}_{10}(\text{OH})_2$  and biotite which also contains Mg and Fe. Muscovite is resistant, like the feldspars, but biotite is less so.

<sup>1</sup> These formulae are better than the double-oxide formulae such as  $\text{K}_2\text{O} \cdot \text{Al}_2\text{O}_3 \cdot 6\text{SiO}_2$  for  $\text{KAlSi}_3\text{O}_8$ . Our way of looking at these silicates has completely changed now that we know through X-ray work about the atomic arrangement inside the crystal. For the present purpose all that concerns us about this arrangement is that ions of similar size can replace one another in the crystal. Thus calcium replaces sodium (which has the same size) in  $\text{NaAlSi}_3\text{O}_8$  and simultaneously one aluminium replaces silicon, where again the sizes are similar; electrical charges now balance. Cu, Zn, Co,  $\text{Fe}^{++}$ , Mn can replace the small Mg ion, but cannot replace the bigger ions K, Na, or Ca; feldspars therefore provide only K, Na, and Ca, while magnesian minerals provide many elements besides Mg.



(4) *Apatite*  $\text{Ca}_5(\text{PO}_4)_3\text{F}$  is present in some soils. This is the original source of phosphorus in igneous rocks. However, it does not survive weathering for long, and is very rare in Victorian soils.

(5) Besides the useful minerals mentioned, *iron oxide* and some other very resistant minerals are also present in small amounts. *Zircon* and *tourmaline*, compounds containing zirconium and boron respectively, are common examples of these.

A soil with a good supply of primary silicates can remain chemically rich over many years of cropping. An experiment by Graham in America shows this clearly. He isolated 1500 grams of the fraction from  $5\mu$  upwards from each of a dozen soils, mixed it with 20 grams of an acid clay and kept the mixture moist in pots for five months to give the minerals time to react with the clay, then grew soya beans in each pot. Mixtures from sand-plus-silt fractions with rich primary minerals gave an excellent harvest, while those poor in primary minerals (that is, with little but quartz) gave no crop at all. Thus the plants growing on the rich material got all the necessary nutrients from the fine sand and the coarser silt fraction ( $5\text{--}20\mu$ ). This does not mean that the soils with the poor sand-plus-silt were necessarily infertile; they may have had a store of nutrients in the colloid fraction (which was removed for this experiment); they may have had an excellent physical structure. The conclusion is rather that the right primary minerals can guarantee the chemical fertility. The experiment is so striking that it is strange that this section of the knowledge of soils has been so neglected. The experiment also shows the powerful weathering property of acid clay, which acts presumably by the reaction  $\text{M-mineral} + \text{H-clay} \rightarrow \text{H-mineral} + \text{M-clay}$ , where M is a metal.

Primary minerals weather slowly in cool climates, where they are therefore common—for example in Great Britain. They are much rarer in equatorial climates where they are constantly attacked by warm water; on this account, they are particularly valuable if present in appreciable amounts. Young soils—formed, for example, from volcanic material—are rich by virtue of their augite and other quickly available minerals. Old soils may be completely infertile for shallow-rooted crops, once the minerals have gone and soluble compounds have been leached away, but they may still support big trees which have their deep roots in contact with freshly decomposed rock.

#### SAND FRACTIONS OF VICTORIAN SOILS

Rich sand fractions are not common in Victoria, except in the mountainous country. In the north, the sediments from which the soils were formed are themselves poor in primary silicates, so the soils also have a poor supply. This does not matter much, since leaching has been so slight. In the wetter



districts of the south many soils have lost their original reserves. The soils on basalt are interesting to consider (Table 26). The young soil on volcanic tuff (1) contains augite, olivine, and basaltic glass besides ample feldspar; the basaltic glass is particularly valuable. The onion-growing soils of Koroit and the

TABLE 26  
MINERALS IN THE FINE SAND FRACTIONS OF VICTORIAN SOILS,  
USING A SAMPLE OF 500 GRAINS

	1	2	3	4
Place .. ..	Birregurra	Terang	Nilma	Orbost
Soil Type .. ..	Mt. Gelli- brand clay loam	"Buckshot plains"		
Description .. ..	Immature basalt tuff	Podzolic with iron- stone on pliocene basalt	Krasnozem on oligocene basalt	Podzol on Quaternary sand
Depth: inches .. ..	0-6	12-18	10-20	4-14
Quartz .. ..	311	427	458	464
Plagioclase .. .. (Ca-Na feldspar)	83	17	7	15
Iron oxide .. ..	12	15	12	4
Augite .. ..	6	0	0	0
Olivine .. ..	11	0	0	0
Basaltic glass .. ..	34	0	0	0
Zircon .. ..	3	2	3	6

The remaining grains in the total of 500 consist of tourmaline, an amorphous boron-containing material, and sponge spicules, which are composed of silica and are the inorganic residues of fresh-water sponges.

Warriors in the Western District contain reserves like this. The podzolic "Buckshot plains" of the further Western District (2) and the grey clays of the nearer Western District contain only a little feldspar, and no other minerals of value. The upper horizons of the krasnozem (3) of nearer Gippsland have



been so severely weathered that they have lost practically all their primary silicates, and are even poorer in this respect than the neighbouring podzols (4) on sedimentary materials.

The young soils on tuff have been quoted as having a supply of useful minerals in the fine sand. Another example is found in the Otways and the South Gippsland hills, where dairy farms have replaced a dense forest. The Jurassic sandstones of these areas are remarkably rich for sedimentary rocks; the slopes are steep and the soils immature. The sand fractions contain feldspars, both of K and of Ca plus Na, in abundance. Good reserves are also present in a few soils derived from young alluvium washed from the igneous rocks of the mountains.

#### *Minerals Brought by the Wind*

While the main interest of this subject is the practical one of fertility, the study of the fine sand also shows how much material is brought by the wind. The quartz of basaltic soils and the universal sponge spicules, zircon and tourmaline, must have been so brought. The wind-blown quartz of basaltic soils may make up as much as 40 per cent of the upper horizons.

#### COPPER AND COBALT IN WESTERN AUSTRALIA

In the south-west of Western Australia large areas of land are deficient in copper and cobalt (pp. 187-8). Healthy patches of soil in such country have been found to be associated with the presence of small amounts of ferro-magnesian minerals.



## CHAPTER XIV

### ACIDITY AND ALKALINITY

#### PLANTS AND pH

ALL PLANTS ARE AFFECTED BY THE DEGREE OF ACIDITY OR ALKALINITY OF THE soil. Some can grow over a wide range of pH, some are sensitive to acidity, others sensitive to alkalinity. We may roughly divide the pH range of soils into five parts: strongly acid, from 4 (or even less) up to 5.5; moderately acid, 5.5 to 6.5; neutral, 6.5 to 7.5; moderately alkaline, 7.5 to 8.5; strongly alkaline, 8.5 to 10. These values are commonly determined by electrometric methods, but may also be measured approximately by indicators (see p. 199) while Comber's test, though it has no exact relation to pH, is quick and useful on the acid side. In this the soil is shaken with Comber's reagent, a 10 per cent solution of ammonium thiocyanate in alcohol; the solution clears quickly and gives the red colour of ferric thiocyanate if the soil is acid. Strongly acid soils give a deep red, slightly acid soils a pale red, and soils of pH 7 or more give no colour. Table 27 shows the pH relations of some plants of importance to

TABLE 27

#### SOME RELATIONS OF PLANTS TO pH

<i>Tolerant of Acidity</i>	<i>Tolerant of Alkalinity</i>
White clover	Oats
Subterranean clover	Rye
Lupin	
Oats	
Bent grass	
Rye	
Yorkshire fog	
<i>Intolerant of Acidity</i>	<i>Intolerant of Alkalinity</i>
Sugar beet	Chestnut
Cauliflower	Rhododendron
Red clover	Potato
Lucerne and medicks	Subterranean clover
Spinach	Tea
Onion	Coffee

farmers and gardeners. This list is far from complete; only a few well-marked examples are chosen. The hydrangea might also be listed among the plants that need an acid soil. It certainly grows to a fine bush in the limed gardens of Melbourne, but its leaves are commonly pale green and obviously poorer than



the fine dark-green leaves of the same varieties growing on the acid soils of Gippsland or Mount Dandenong. Besides these relations of crops, the native species or common weeds may also be so closely associated with a limited range of pH that they may be used as indicators. One must remember, however, that climate and recent management and many other chemical and physical properties of the soil besides pH interact in determining the vigour of a species. Thus, many very acid soils are also very sandy; the majority of highly alkaline soils are also saline. With these limitations in mind, in grassland we find subterranean clover on acid soil, burr medick on neutral or alkaline soil; among weeds, chickweed is intolerant of acidity while sorrel is highly tolerant. However, even this last relation has often been pushed too far. Sorrel need not indicate acidity; it tolerates, but does not require, a low pH. It is not destroyed by lime, but it can be suppressed by more desirable plants when the fertility is raised. Among native shrubs, while little is known of their requirements, it is likely that many require a fairly low pH, and the alkalinity of many garden soils is the reason for their failure on transplanting.

#### CHEMISTRY OF SOIL pH

These relations between pH and growth may be more easily understood if we form a chemical picture of how these values are themselves caused, and what other properties are associated with them.

The pH of a soil is the same as that of its colloidal fraction. In the great majority of cases clay preponderates greatly over organic matter, so this discussion will be in terms of clay.

If some clay is isolated from soil and washed several times with dilute acid (say N/100 HCl) hydrogen replaces all other cations, which are removed in the filtrate. The free HCl can then be washed out with aqueous alcohol, leaving the pure acid clay behind. This is an insoluble weak acid, which in *suspension* in water may be as acid as pH 3.5; since it is insoluble, the supernatant *solution* is neutral. The clay of a normal soil, however, contains other cations than hydrogen; the acid clay is partly or wholly neutralized—or *saturated*, as it is sometimes called. In so far as the exchangeable hydrogen is replaced by Ca, Mg, K, or Na, the colloid tends to be alkaline—just as sodium acetate is alkaline, because acetic acid is weak. The effect may be shown for an extreme (hypothetical) case of a particle saturated with sodium and of formula  $\text{Na}_{200}\text{X}$ . Such a particle dissociates in water giving sodium ions and leaving a negatively charged ion, which is immediately hydrolysed by water giving free alkali; thus—





The alkali is produced for the same reason as with sodium acetate—the hydrogen ion sticks firmly to the colloid, forming an almost undissociated acid, analogous to acetic acid, while some of the sodium compound ionizes—in the above hypothetical case, five per cent of the sodiums dissociate and so ten hydroxides come into the soil solution, this being the proportion indicated by experiments. If excess sodium salt is present, reaction (i) above is reversed, and at the same time the colloid is flocculated and alkaline hydrolysis is suppressed. Such a saline soil is called a *Solonchak*. If salinity is not great, a soil high in exchangeable sodium is highly alkaline (see Table 28, p. 168). Such alkalinity in its turn disperses the negative colloids still more (alkalies stabilize negative colloidal solutions, acids flocculate them)<sup>1</sup>. The organic matter comes nearly into true solution and takes on a very dark colour—like many complex organic acids it is intensely coloured in an alkaline environment. This dark colour gives to the soil the name “black alkali”.

A “black alkali” soil, with its pH of 9.5 or so, will yield some normal sodium carbonate,  $\text{Na}_2\text{CO}_3$ , on extracting with water. This may be determined by its alkalinity to phenolphthalein. This carbonate is necessarily there as the result of the production of  $\text{CO}_2$  in an alkaline environment. It is thus wrong to say that black alkali is due to sodium carbonate; if the small amount of free carbonate could be removed, the black alkali would still remain, so long as the pH remained high. Bicarbonate ion can always be extracted from high-sodium soils. “White alkali”, by the way, is a “popular” term in agriculture for salt, usually  $\text{NaCl}$ , appearing on the surface as a white crust. The term is incorrect and indefensible but will probably persist for some years to come.

Calcium-saturated clays are also alkaline, but to a smaller extent because calcium does not dissociate from the colloid so readily as sodium. We could write for calcium clay:—



Calcium thus produces one-fifth as much alkali as sodium. While the pH rises to 10 in Mallee subsoils under the influence of exchangeable sodium, it is doubtful whether exchangeable calcium alone can produce a pH as high as 9 in nature. The common limit in sodium-free soils is 8.4, which is the figure given by  $\text{CaCO}_3$  in equilibrium with atmospheric  $\text{CO}_2$ ; the pH of  $\text{CaCO}_3$  in the soil must be lower since  $\text{CO}_2$  is more concentrated in the soil than in the atmosphere.

Magnesium is similar to calcium in this respect but causes rather higher pH values, on account of the greater dissociation of the ions from the clay particle.

<sup>1</sup> The dispersed colloid may dry to form well-marked vertical columns with rounded tops in the subsoil. A profile with such round-top structure is often called by the Russian name *solonetz*.



$\text{MgCO}_3$  also is more soluble and so gives a higher pH than  $\text{CaCO}_3$ . Potassium seldom is an important constituent of the exchangeable ions, though samples have been found, as in the Riverina, where it predominates; its effect has not been properly studied, but it is certainly less powerful than sodium in producing alkalinity.

The pH of a soil is decided by the relative amounts of exchangeable hydrogen and each of the four metals Ca, Mg, K, Na.<sup>2</sup> Not many local analyses quote exchangeable hydrogen. There are two reasons for this. Firstly, Australian soil surveys have specialized on the irrigated areas where pH is high and therefore no hydrogen is exchangeable at pH 7, which is the most sensible point at which to measure it; secondly, there is no general agreement on the method of measurement—the pH of the leaching solution and the other conditions of extraction must be standardized before results of different workers are comparable. To give an idea of its order, Tasmanian podzolic soils of pH 5.5 were found to have equal amounts of exchangeable Ca and H, the calcium making up about two-thirds of the metallic ions.

## LIMING AND DE-LIMING

### I. THE PROBLEM OF ACIDITY

Most of the soils in other parts of the world which are benefited chemically by lime have a pH below 5.5. Such values are common in the well-watered parts of Australia, and figures below 4 have been recorded in coastal Gippsland. We are concerned therefore with the effect of acidity and the reason for good results from lime.

An acidity of pH 5.0 means only one part of acidic hydrogen in 100,000,000. This seems too mild to do any direct damage to the plant. In fact, when plants are grown in complete nutrient solution the pH can be adjusted to 5 without harm. However, plants seem to absorb metallic ions by producing a lower pH at the surface of the root than exists in the soil, so where the contrast between root and soil is weakened, the absorption of calcium, potassium, and so on becomes more difficult. The badness of acid soils is also connected with other factors, which will now be mentioned.

The first factor is that acid soils are usually poor in the necessary nutrients, particularly in calcium and magnesium. The application of lime supplies the necessary element calcium; dolomite, which is preferable on many soils, also supplies magnesium. This is an important gain, but it cannot explain all the observed effects of lime, since calcium applied as sulphate will not have the same effect as an equal amount applied as carbonate.

<sup>2</sup> Aluminium is sometimes mentioned as an exchangeable ion. It is doubtful whether this view is correct; if it is, the aluminium would make for a low pH on account of hydrolysis. Other metals occurring as exchangeable ions in minute amount can be neglected here.



*Aluminium and Manganese*

At low levels of pH, poisonous elements which are normally present in only very low concentrations can come into solution in important amounts. The two most likely to be excessive are aluminium and manganese. Aluminium is least soluble near the neutral point; its concentration in a soil depends not only on the pH but on other factors, especially the nature of the clay, sesquioxidic clays providing more than siliceous clays at the same pH. However, a fairly representative figure for solubility is a rise from 0.2 parts per million at pH 5.5 to 15 parts at pH 4.5. This latter figure is more than many plants can tolerate. Chickweed, a plant associated with fertile soils, is poisoned by one eighth this amount of aluminium. Barley is similarly sensitive. Both these plants are intolerant of acidity. On the other hand, many plants can tolerate large amounts of aluminium. For example, hydrangeas can make good growth on acid soils and may contain as much as 1 per cent of aluminium in their dry matter. Manganese, a necessary element, also rises to poisonous concentration in some acid soils, especially if they remain moist and the rain is not heavy enough to wash out soluble salts.

Liming a soil reduces the concentration of both these elements below the danger point.

*Potassium and Phosphorus*

Other virtues are often attributed to lime; for example, it is said to increase the availability of the potassium and phosphorus already in the soil. The evidence in favour of this indirect effect on potassium is scanty, and the theoretical explanation which is usually given is probably wrong. With phosphorus, the effect is important in some soils which are high in free ferric oxide; lime is applied in New Zealand, particularly in the North Island, with the object of improving the response to superphosphate (see p. 177).

*Micro-organisms*

Raising the pH of the soil with lime also influences the microbial flora, leading in some soils (though not in all) to a quicker production of nitrate from organic matter. Whether this is a good thing or not depends on the system of management which the farmer follows. Other useful processes may also be stimulated, though this subject is not very well known. Micro-organisms, like plants, may be either sensitive or tolerant to either high or low pH.

*Results in Southern Victoria*

Few positive results have been obtained with lime in Victoria except where the pH is very low, as at Inverloch (4.2). The pioneering treatment includes top-dressing with superphosphate, which makes up some of the deficiency in



calcium. Besides, the important plants of the podzolic country—oats, maize, subterranean clover, rye grass, white clover, potatoes—are normally associated with acidic soils, and do not make more growth when the soil is limed. After all, it is the plant and not the soil which needs the lime. However, some observers claim that animals appear to be healthier when grazing on limed than on unlimed pastures.

The popular term “sour” is generally applied to infertile soils, and has no connection with acidity. A soil may be called “sour” and be highly alkaline; it may even be neutral but infertile through waterlogging or some other cause. The word only causes confusion, and had better be dropped altogether.

#### *“Lime Requirement”*

A great deal of work has been done in many countries in estimating whether lime should be added to a soil, and if so, how much. A common practice, before pH was generally understood, was to estimate the “lime status” of a soil by treating a sample with hydrochloric acid, measuring the  $\text{CO}_2$  that came off, and calculating this as so much  $\text{CaCO}_3$ . When  $\text{CaCO}_3$  is below about 0.1 per cent this method is difficult to carry out and is fallacious in any case, since the HCl may split off small quantities of  $\text{CO}_2$  from organic compounds which will thus be wrongly recorded as  $\text{CaCO}_3$ . In recent years, analysts have tried instead to determine how much lime is needed to bring the soil to neutrality (pH 7). Anyone with experience of the district can then interpret the result and advise how much lime ought to be applied, if any; it is usually sufficient to add enough lime to raise the pH only to 6 or even less. If any finely-divided  $\text{CaCO}_3$  can be seen remaining from previous applications, it is obviously useless to apply any more. Some crops flourish only at a pH of 6 or more. On some soils the cost of bringing the pH to that level may not be worth while, and the proper treatment is therefore to use the land for acid-tolerant crops only.

The effect of added lime on the pH is shown in Fig. 35. Soil A is intensely acid, but has a low buffering power and is easily brought to neutrality. Soil B, though originally not so acid, needs more than twice as much lime as soil A in order to reach a pH of either 6 or 7. These curves have the shape one would expect for the addition of an alkali to a weak polybasic acid, which is what the colloid clay consists of. They represent in fact complex buffer systems. Soil B contains more colloid per acre, so resists any alteration of pH more effectively than soil A.

#### *Physical Effects of Lime*

Chemically, lime destroys acidity, lowers the activity of metals including aluminium and manganese, and supplies the necessary element calcium which becomes an exchangeable cation. Physically, its effect also is complex. It pro-



vides calcium for the soil solution, and so helps to keep the clay from dispersing. In this regard, however, gypsum is much more efficient. But lime may have a further long-range effect by altering the quality of some of the organic matter and so improving the structure, in a way that is little understood as yet.

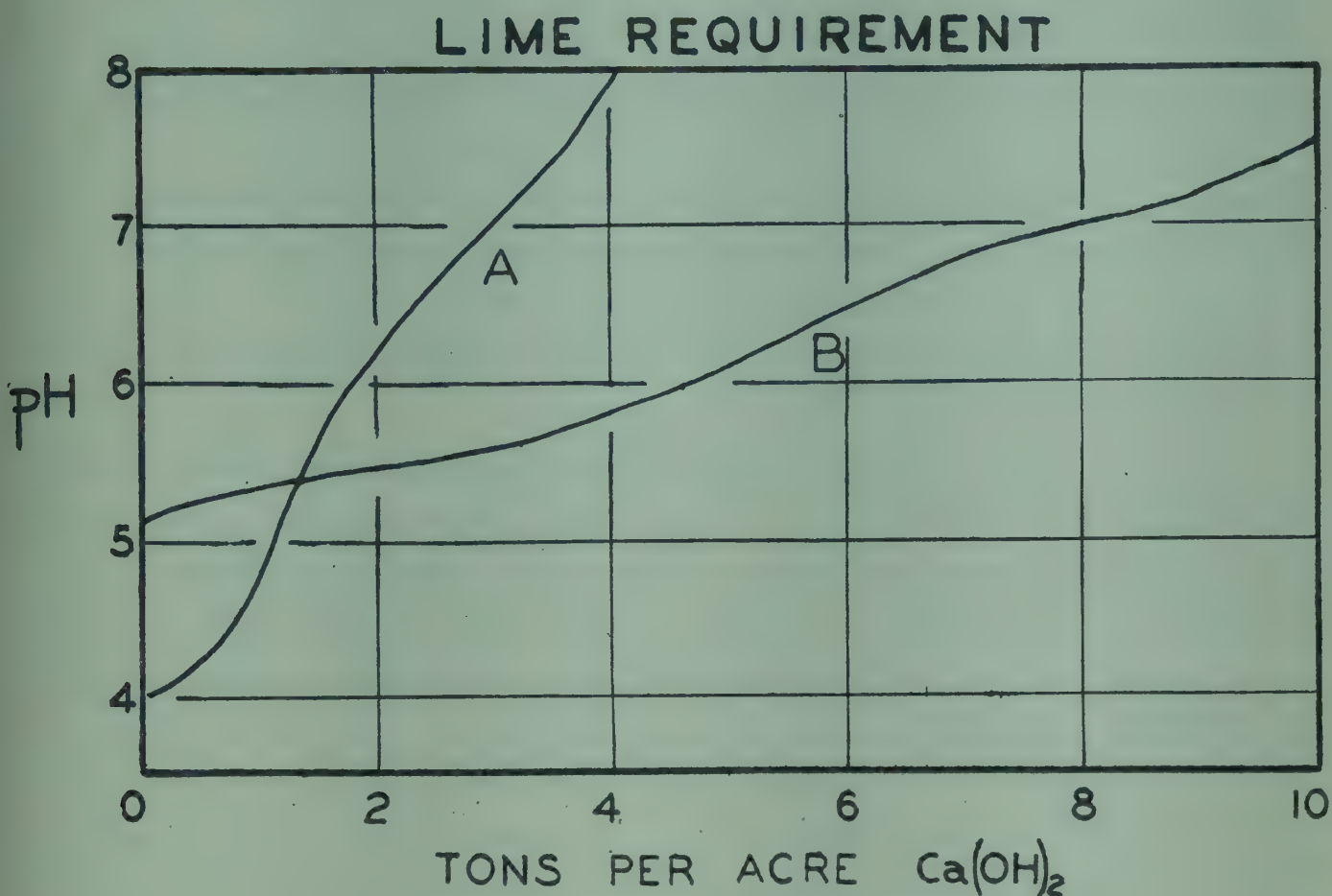


Fig. 35. Effect of added lime on the pH of two acid soils.

It is often said that lime not only loosens clayey soils but consolidates sandy soils; sometimes the analogy is made of the setting of lime and sand to make a mortar—which is hardly a recommendation! In any case, this claim has no foundation. Calcareous sands are common, both near the coast and in the dry inland, and they are no firmer than their lime-free neighbours, nor is there any scientific reason why they should be at all different.

#### *Forms of Lime*

The term *lime* includes three compounds—calcium oxide, hydroxide, and carbonate. In the long run all three of these forms have the same effect, if they are applied in chemically equivalent amounts—that is, 560 lb. per acre of  $\text{CaO}$ , 740 lb. of  $\text{Ca(OH)}_2$ , and 1000 lb. of  $\text{CaCO}_3$ . The oxide turns to the hydroxide within a few hours of application, and the hydroxide if in excess turns to carbonate within a few weeks. However, the oxide or hydroxide reacts with soil more rapidly and produces a much higher pH at first than does the carbonate; whether this is good or bad depends on the particular case. Choice



between these three depends more on their relative cost than on chemical differences.

## 2. DE-LIMING A CALCAREOUS SOIL

A soil may contain a reserve of  $\text{CaCO}_3$ , either naturally or in consequence of heavy applications of lime. In either case this reserve may be recognized by effervescence on the addition of fairly strong hydrochloric acid (2N to 5N). Some lime-rich soils are highly fertile, as for example the chernozems of Russia. However, it is far from true to say that "limestone land is good"—a statement, incidentally, that ignores the many leached soils formed on limestone. Many calcareous soils fail to support healthy growth in plants because some element is of low availability; this may be phosphorus, zinc, iron, or manganese. Plants differ greatly from one another in their tolerance of high pH. Those growing in dry climates are commonly tolerant.

Where the pH is too high, various acidifying agents can be used, including aluminium sulphate and sulphur, which is oxidized in the soil to sulphuric acid. Soils containing 1 per cent or more of  $\text{CaCO}_3$  cannot be acidified by this means, on account of the cost. On such soils we have to grow tolerant crops, or use some other method than changing the pH for curing any physiological trouble that may develop.



## CHAPTER XV

### CALCIUM, MAGNESIUM, POTASSIUM, SODIUM

THESE FOUR ELEMENTS ARE NORMALLY DETERMINED IN THE EXTRACTS OBTAINED by leaching with ammonium acetate in the analysis of exchangeable ions. Several other elements, including manganese, zinc, and copper, are also present in these extracts in very small amounts, but are not usually determined. The above four are calculated as so many "milli-equivalents (or m.e.) per cent" in the soil. Thus if an extract made by washing 10 grams of soil with ammonium acetate contains 10 milligrams of calcium, instead of recording  $\text{Ca}=0.10$  per cent (or  $\text{CaO}=0.14$  per cent) we divide by the equivalent weight (20 for Ca, 28 for CaO) and multiply by 1000 since the milli-equivalent is a more convenient unit than the equivalent for dealing with small quantities. Thus we get exchangeable calcium equals 5.0 m.e. per cent. Similarly we might get the respective values for Mg, K and Na of 3.5, 1.0, and 0.5 m.e. per cent. These are again recalculated so as to express each element as a percentage of the total; in this case 50, 35, 10 and 5 per cent respectively.

These figures for exchangeable ions have two main uses. Firstly, their relative amounts affect the physical nature of the clay. Secondly, the total amount of the exchangeable element, with reservations regarding potassium, gives an estimate of the element available to plants. Regarding the first point, sodium and calcium have antagonistic effects. If sodium reaches 20 per cent it makes the clay easily dispersed and gelatinous when wet, and therefore slow to drain. Calcium is more effective than magnesium in countering this tendency; unfortunately, high-sodium soils are commonly low in calcium and higher in magnesium (Table 28). The low calcium in the calcareous subsoil of Merbein is interesting.<sup>1</sup> In this highly alkaline environment the  $\text{CaCO}_3$  has a very low solubility, while sodium salts are present to the extent of .2 per cent; the active mass of the sodium in solution is overwhelmingly greater than that of the calcium, so it dominates among the exchangeable ions. Given free competition at equal concentrations, calcium would occupy about ten places on the clay surface for every one occupied by sodium. High-sodium soils have been reclaimed by adding gypsum and flooding, so removing the sodium sulphate ( $100 \text{ CaSO}_4 + \text{Na}_{200}\text{X} \rightarrow \text{Ca}_{100}\text{X} + 100 \text{ Na}_2\text{SO}_4$ ). Theoretically, we might replace 5 m.e. per cent of sodium by adding 5 m.e. per cent of gypsum, or 0.43 per cent of the soil. This equals 8 to 9 tons per acre for treating the surface foot. In fact amounts of this order are sometimes applied. (Compare p. 161).

<sup>1</sup>To determine exchangeable calcium in a calcareous soil needs special methods, which allow for dissolved  $\text{CaCO}_3$  (which is *not* exchangeable).



between these three depends more on their relative cost than on chemical differences.

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These figures for exchangeable ions have two main uses. Firstly, their relative amounts affect the physical nature of the clay. Secondly, the total amount of the exchangeable element, with reservations regarding potassium, gives an estimate of the element available to plants. Regarding the first point, sodium and calcium have antagonistic effects. If sodium reaches 20 per cent it makes the clay easily dispersed and gelatinous when wet, and therefore slow to drain. Calcium is more effective than magnesium in countering this tendency; unfortunately, high-sodium soils are commonly low in calcium and higher in magnesium (Table 28). The low calcium in the calcareous subsoil of Merbein is interesting.<sup>1</sup> In this highly alkaline environment the  $\text{CaCO}_3$  has a very low solubility, while sodium salts are present to the extent of .2 per cent; the active mass of the sodium in solution is overwhelmingly greater than that of the calcium, so it dominates among the exchangeable ions. Given free competition at equal concentrations, calcium would occupy about ten places on the clay surface for every one occupied by sodium. High-sodium soils have been reclaimed by adding gypsum and flooding, so removing the sodium sulphate ( $100 \text{ CaSO}_4 + \text{Na}_{200}\text{X} \rightarrow \text{Ca}_{100}\text{X} + 100 \text{ Na}_2\text{SO}_4$ ). Theoretically, we might replace 5 m.e. per cent of sodium by adding 5 m.e. per cent of gypsum, or 0.43 per cent of the soil. This equals 8 to 9 tons per acre for treating the surface foot. In fact amounts of this order are sometimes applied. (Compare p. 161).

<sup>1</sup>To determine exchangeable calcium in a calcareous soil needs special methods, which allow for dissolved  $\text{CaCO}_3$  (which is *not* exchangeable).



Firstly, plants can get potassium from certain non-exchangeable forms. No chemical method has been established for determining these forms, but we can be sure that they exist, since a succession of crops grown on the same land has been shown to remove more potassium than was there originally in the exchangeable form. Possibly the potassium present in the crystal lattice of very fine colloid particles is mobile enough to migrate to the outside and so to replenish the store of the exchangeable element. All we can say definitely at present is that no soils with as much as 0.4 m.e. per cent are deficient, while below this figure the supply may be anything from good to bad.

Secondly, much depends on the use of the land. Stock-raising does not drain the land of its potassium; but the removal of hay and of some crops including flax and potatoes is much more serious (see Table 30). A soil might just be able to keep replenishing from low-grade reserves the four or five pounds an acre removed each year in normal dairying but might fail to do so after two or three crops of hay had been sold off the property. Even the normal drain of fertility from the outer paddocks to the central dairy may be enough to starve the land of potassium if the washings of the shed are not returned. The "Hosier system", developed in England, deals with the problem by moving the milking sheds around the property.

TABLE 30  
BALANCE SHEETS FOR POTASSIUM IN AN ACRE OF LAND

	<i>Pounds</i>
Normal total in soil, 0-6 inch.....	2,000-20,000
Exchangeable, 0-6 inch.....	150-1,000
Removed in 25-bushel wheat crop.....	6.3
Annual removal, cropped once in 3 years.....	2.1
Removed in 2 fat lambs annually.....	0.2
Removed in 250 gals. milk and calves sold off dairy farm (one cow to 2 acres).....	3.7
Removed in 4-ton potato crop.....	22
Removed in 2 tons oaten hay.....	30
Lost in drainage water (2 p.p. million), 5 inches annually in Gippsland.....	2

Potassium when applied as a fertilizer is mostly adsorbed on the colloids, and little remains in solution—5 to 10 parts per million for a normal soil; except in very sandy soils, only a small proportion is lost in the drainage. This may be a disadvantage in a cultivated orchard, where there are few roots at the surface and where the fertilizer may fail to reach the lower layers in which most of the roots are. Apart from this difficulty, potassium in many soils has the ideal arrangement for a nutrient—a soluble supply is always present, just large enough for the crop's needs but not so large as to risk serious leaching.



In some soils, however, potassium reverts rapidly to a non-exchangeable form of fairly low availability. On such a soil the residual effect of added fertilizer is low, and only after the second-class capital has been built up by several years of applying the element does the soil become able to provide for current needs. No way is known at present of diagnosing the potassium-reverting power of a soil apart from field trials.

Potassium like other elements is commonly more plentiful in heavy than light soils. Many light soils in southern Victoria contain less than 0.1 per cent of the element soluble in boiling HCl, which is poor by overseas standards. However, not all heavy soils are good. Some clays contain ample supplies of non-exchangeable potassium which can guarantee a fair supply of the exchangeable ion; others do not. It depends on the kind of clay. Kaolinite has no place for potassium in its lattice, and accordingly krasnozems are often low in potassium though high in clay. Where the clay colloid contains hydrous mica, it is rich in potassium.

### SODIUM

Recent work overseas has shown that the growth of beets and some other vegetable crops is increased by the application of sodium chloride or sulphate. Asparagus, in spite of the popular belief, is not improved by sodium salts. There is no local record of the usefulness of added sodium salt; the annual fall of over 20 pounds of sodium chloride per acre with the rain in southern Victoria would probably stultify any experiments.

### *Salt*

The chief interest in sodium is in the damage done by excess salt. A high concentration of electrolyte in the soil can limit growth or even kill a crop; the danger point depends on the electrolyte and on the plant. While any electrolyte can be harmful, the dominant one in southern Australia is sodium chloride, which will be called "salt" in this discussion. This commonly makes up two-thirds or more of the total soluble solid (Table 31), bicarbonate and sulphate ions being also present in saline soils. In the Mildura area sulphate may exceed chloride, though here too in highly saline soils chloride prevails. Sulphate is also often dominant in California.

*Relative Tolerance of Plants:* Plants differ greatly in their tolerance of salt. Lucerne and strawberry clover are tolerant, as are many grasses. Orange trees at the other extreme are highly sensitive. The most tolerant plants of all include some useful saltbushes, some low-grade fodders like barley grass, and some useless species, for example samphire. Whereas a concentration of 0.1 per cent in surface soil is a limit for general purposes, the highly tolerant or salt-loving plants thrive at 1 per cent of salt. However, even 0.1 per cent is liable to lower



the yield, especially because salt moves easily with irrigation, and may become concentrated in patches. For the fairly tolerant grape-vine in the Murray Valley, the best growth requires less than .07 per cent of NaCl, which is determined in the second or third foot, since the salt in the top foot is extremely variable.

TABLE 31  
SALT IN KERANG CLAY  
(REPRESENTATIVE OF MOST OF MURRAY SYSTEM)  
AND IN MERBEIN CLAY LOAM (MILDURA AREA)

Soil type	Depth inch	Total soluble p.p. 100,000	Ions, parts per 100,000						
			Cl	SO <sub>4</sub>	HCO <sub>3</sub>	Ca	Mg	K	Na
Kerang clay	13-30	1826	946	155	27	34	62	5	525
Merbein clay loam ..	22-38	340	18	178	49	6	5	4	90

These figures are typical as regards *relative proportions* of ions in the total solid, not as regards total solid itself.

*Occurrence:* Toxic amounts of salt occur mostly in semi-arid climates. Millions of acres east of the main wheat belt of Western Australia are naturally too saline for agriculture, and cannot be reclaimed. Even greater areas in the Mallee of South Australia and Victoria, and also the lower Goulburn Valley in Victoria and adjoining land in the Riverina, contain dangerous amounts of salt in the subsoil, where it has accumulated from the rain over the centuries. The climate is just wet enough to wash most of the salt down to three or four feet, but not wet enough to wash it right out of the profile. A concentration of 0.15 per cent or more is common from two feet downwards. Under irrigation a water-table is formed between 5 and 10 feet of the surface, and this ground-water may contain 1 per cent or more of salt. Heavy watering may cause the water-table to rise still further on the lower-lying ground; eventually the salt water may climb through the uppermost two feet by capillarity, the more easily the less vigorous the plant cover, and appear as a white crust on the surface, which becomes soft and powdery. Salt has been concentrated by evaporation at the surface in many irrigated districts. Large areas of such artificially salted land occur near Kerang, and are marked by samphire and dillon-bush.

High concentrations of salt also occur in southern Victoria. The subsoil of the near Western District contains .3—.4 per cent NaCl in the third foot.



Salt lakes also are common—Lake Murdeduke, lying in the dry belt, is saturated with salt, being a centre of internal drainage. Actual damage by salt, however, is mostly confined to small patches no more than an acre in extent lying at the base of slopes, which may be seen in the districts of Hamilton, Berwick, and Sale. This is associated with a podzolic soil, with a permeable surface horizon (commonly a sandy loam) lying over a heavy clay. Water flows gradually down the slope on top of this clay subsoil, and carries the salt of the rain with it. This flow is checked at the foot of the slope, and in places salt water rises by capillarity and evaporates at the surface to produce eventually .5 per cent or more of NaCl in the surface soil. Such patches are either bare or carry typical tolerant plants—mostly buckshorn plantain, sometimes accompanied by salt-marsh plants such as samphire. Some of these salt patches have appeared after the destruction of eucalypt cover on the higher land. Transpiration has been reduced, and more water then seeps to the foot of the slope. It remains to be seen whether the substitution of vigorous pasture for native grasses will destroy this effect by increasing transpiration again.

*Reclamation under Irrigation:* Where the soil is permeable, as in the Mallee types along the Murray, the salt may eventually be washed out of the profile if the drains are used. The land at Kerang, however, will not repay the cost of drainage. Some has been reclaimed by establishing a vigorous winter pasture with superphosphate. The irrigating water washes the salt from the surface, and the pasture by transpiration keeps down the saline water in the subsoil, and by shading the surface helps to prevent the rise of ground water. So long as watering is just heavy enough and not too heavy, irrigated land can remain in production, in spite of the apparent resemblance to living on an active volcano. The irrigation water itself must be low in salt. Any water above 0.1 per cent of salt is dangerous, though the limit could be higher with a permeable soil and good rainfall. Fortunately the water of the Murray system has far less salt than this.



## CHAPTER XVI

### PHOSPHORUS

AUSTRALIAN SOILS ARE ALMOST ALL POOR IN PHOSPHORUS, THE MAIN EXCEPTIONS being in subtropical New South Wales and Queensland. In Victoria, only a few small areas of river flats and immature volcanic ash contain a good supply. This general poverty is well illustrated by the fact that the dividing line between “good” and “medium” figures for the total reserve of phosphorus soluble in hot concentrated hydrochloric acid is 0.20 per cent of  $P_2O_5$  (0.09 per cent of phosphorus) in the opinion of European workers, and 0.10 per cent of  $P_2O_5$  (0.044 per cent of phosphorus) in the opinion of most Australians. The typical Victorian level is .02 to .03 per cent of phosphorus, but many sandy soils have less than .005 per cent. An Australian, accustomed to seeing big increases in yield from the use of superphosphate, learns with surprise from the English writer Comber that “the effects of phosphorus concern factors of quality rather than quantity”.

#### SUPERPHOSPHATE

Phosphorus is usually applied to the soil as *superphosphate*, prepared from rock phosphate and sulphuric acid. The usual equation quoted for the reaction is:



The rock phosphate is really a more basic material than the tricalcium phosphate given by this conventional formula, being hydroxyapatite— $Ca_5(PO_4)_3(OH)$ —in which much of the hydroxide is replaced by fluoride. If we write this as  $3 Ca_3(PO_4)_2, Ca(OH)_2$ , we can see that additional sulphuric acid must be used, so the percentage of  $CaSO_4$  in the product is rather higher than is given above. This of course is a minor matter. The essential thing is that enough acid has to be added to produce the water-soluble acid phosphate. This phosphate has a pH of 3.6 in concentrated solution. The next calcium phosphate in order of basicity,  $CaHPO_4$ , is approximately neutral in reaction and is only slightly soluble in water (about 100 parts per million at pH 7) but it dissolves in neutral citrate solutions, citrate ion having the remarkable power of removing calcium from the system to form a complex calci-citrate, so allowing more of the phosphate to dissolve.

Superphosphate had to meet two prejudices connected with the above reaction: firstly, it is soluble in water and so might be washed out of reach of the roots in wet climates; secondly, it is acidic and so might in time damage the soil (“super” stands for “super-acid”). We may consider these in turn.



### FATE OF APPLIED PHOSPHATE

In spite of its solubility in water, the phosphate of superphosphate is not washed through the soil, but is precipitated close to the surface. This has been proved in many parts of the world by preparing a balance-sheet of phosphate over a period of 30 years or so of supering, and showing that additional phosphate has piled up in the top few inches in amount equal to the difference between the phosphate applied as fertilizer and that removed by plants. Another simple proof is the analysis of drainage water. This is always very low in phosphate, a common figure being 0.2 part of phosphorus per million of water. It would take 20 inches of rain washing right through the soil to carry off one pound of phosphorus per acre in such drainage water. While this is a negligible figure for everyday life, it is important in terms of geological time. For example, if 3 inches of rain percolate through the top 3 feet every year in Melbourne, and this soil contains 2 tons of phosphorus per acre, the time needed to reduce this phosphorus to one half of its value would be  $2240 \times \frac{2}{3} = 15,000$  years. In considering this figure we must remember that weathering and erosion will also play their part during such a long period. Further, the poorer the soil and subsoil become in phosphorus the more dilute the drainage water is likely to be.

A particularly neat method of demonstrating this precipitation at the surface relies on the use of superphosphate made from radio-active phosphorus, which is chemically identical with the inert element but reveals its presence by giving off  $\beta$ -rays. If this radioactive material is applied to a column of soil, and water is added equal to any desired amount of rain, we can measure the concentration of the added phosphate at half-inch intervals down the column. A typical result of such an experiment was that 95 per cent of an application of 180 lb. of phosphorus (as superphosphate) per acre remained in the top inch after receiving the equivalent of  $2\frac{1}{2}$  inches of rain.

### “Reversion”

This change from soluble to insoluble is often called “reversion”. The word suggests that the phosphate turns back to a form like the rock phosphate from which it came; this, however, is not generally true. It must be emphasized that super left to itself does not revert. It only loses its solubility in water if it reacts with some other material—in this case with soil. It is no doubt fortunate that the valuable element phosphorus is not in danger of being washed out. But one naturally asks, Why add all this heavy sulphuric acid—which is not much use in itself—just to make the phosphate soluble, when it is going to be precipitated after all, as soon as the super meets the soil?

We have plenty of evidence that in most parts of Australia superphosphate is better for crops than any other phosphatic fertilizer. But the question remains,



why? The answer seems to be twofold. Firstly, the grains of super may be as large as 2 mm. across, and each of these forms a depot of highly soluble phosphate, some of which may persist without reversion for several weeks. It may be that the plant obtains many of the necessary elements by concentrating on a few favourable spots rather than by gathering minute supplies from all around. The spectacular improvement in wheat-growing in Australia by the use of superphosphate at the rate of half a hundredweight to a hundredweight per acre is due to the fact that the super is not broadcast, but is sown with the seed, and so forms a rich depot for the use of the young plant. However, merely providing fertilizer in granular form is not the whole story; phosphate applied in solution is also effective. The more important answer to the question at the head of the paragraph is that the precipitate formed between soluble phosphate and soil is far more finely divided and dispersed throughout the immediate neighbourhood than any powder that could be prepared from an insoluble phosphate by mechanical grinding. Besides, the precipitate differs from rock phosphate in its chemical composition, as is described below.

#### *Super does not Acidify*

The fear that super might acidify the soil has been widespread. Yet it seems to be unjustified. Several long-term experiments in which super was applied every year have shown the same result—no acidification. For example, the plots of the permanent manurial field at Werribee which have received 2 cwt. per acre of super every second year since 1912 have a mean pH of 5.1 in the surface 4 inches as compared with the control plots with pH 4.8.<sup>1</sup> We may suggest two reasons for this neutral effect of an acidic compound. One is that plants take up the acidic ion  $\text{H}_2\text{PO}_4^-$  as such and so reduce the acidity of the soil. The other reason is more complex and is best seen in the light of the paragraphs which follow.

#### “FIXATION” OF PHOSPHATE

We have seen that phosphate sticks in the top few inches of the soil, and very little gets into solution. So long as the amount in solution is not so low as to limit growth, this is a good thing since it guards against loss. However, the phosphate may be precipitated in a highly insoluble form, and the super will then fail to achieve its purpose. Such precipitation is called “fixation”, and its occurrence depends on the form in which the phosphate is precipitated. This may be one of two kinds—a calcium compound, or an adsorption compound with iron or aluminium.

(a) *Calcium* compounds are the most desirable, if the pH is no higher than

<sup>1</sup> This is an unusually acid figure for a red-brown earth. The common pH found in the district is not far from 6.



about 7.5. Calcium phosphate is then soluble enough to supply the plants' needs, but not so soluble as to incur loss in drainage. But if the soil is rich in  $\text{CaCO}_3$ , especially at a pH of 8 or more, the phosphate is fixed in the form of the basic compound hydroxyapatite, which is a very poor source for plants, since its solubility is extremely low. The only way to liberate such phosphate is to lower the pH—which is usually desirable for other reasons on calcareous soils. Phosphate precipitated by calcium near the neutral point is more soluble than that of rock phosphate; the fluorine present in rock phosphate decreases its solubility very seriously.

(b) Much more attention has been given to the compounds formed in acid soils with *iron* and *aluminium*. These cannot be given simple formulae. The compounds  $\text{FePO}_4$  and  $\text{AlPO}_4$  certainly exist, but they can only be formed in highly acidic solutions. At the pH's which prevail in soils, little aluminium and less ferric iron can be in true solution; but phosphate reacts with their oxides by forming adsorption compounds of general formula  $(\text{Fe}_2\text{O}_3)_n \cdot \text{FePO}_4$ . This compound could be called a "basic salt"; if  $n=30$ , then it can be calculated that the oxide has adsorbed 2 per cent of its weight of phosphate. The reaction can be written—



The phosphate competes strongly with hydroxide for a place on the surface. When thus precipitated it is "fixed" and is of low value for plants.

This reaction incidentally reveals how it is that superphosphate does not acidify soil. The phosphate liberates hydroxide and so may even *raise* the pH. Ferric oxide is too feeble a base to affect the pH itself, so its destruction cannot lower the pH, but it is active enough to destroy the free acid of a phosphate solution and raise the pH in that way.

Aluminium oxide in the free state is not commonly visible in soils outside the wet tropics, but it is present in all clays. It is responsible for fixation by some clays. Kaolinite, which is common in the acid soils of our wetter climates, may also adsorb phosphate. Krasnozems, which contain free ferric oxide and usually aluminium oxide and kaolinite as well, are the worst type for fixing.

If fixation is not too intense, lime may be useful, by virtue of raising the hydroxide concentration and so reversing the reaction (A). The best pH to aim at is between 6.0 and 6.5. Thus the red soils of Mirboo North in South Gippsland give greater growth of pasture with lime and super than with super alone. In this way they differ from the normal grey podzolic soils of southern Victoria, which respond strongly to super but are not benefited by lime in addition. But soils in hotter climates have been reported to fix phosphate so intensely that some plants cannot absorb it whether lime is added or not.



Neubauer tests (p. 129) on such soils have shown that rye seedlings lost more phosphorus to the soil than they extracted. The soils of Lismore (North coast of New South Wales) are an example of this, and are particularly interesting since they are very high in total phosphate (see Table 32). In Hawaii, where fixation is also intense, workers have suggested making briquettes of phosphatic cement and burying them, with the idea that the roots can permeate and use them while the ferric oxide of the soil cannot interfere. No direct treatment of this soil has been effective.

TABLE 32  
PHOSPHORUS DISSOLVED BY BOILING HCl PER CENT OF SOIL

Soil Type	Horizons		
	1	2	3
Hallam loam .. .. inch (podzolic) P, per cent	0-8 (A <sub>1</sub> ) .020	8-12 (A <sub>2</sub> ) .007	30-44 (B) .004
Lemnos loam .. .. inch Shepparton (red brown earth) P, per cent	0-7 (A)	8-28 (B <sub>1</sub> )	28-39 (B <sub>2</sub> )
	.030	.014	.009
Wollongbar .. .. inch near Lismore (N.S.W.) (krasnozem) .. P, per cent	0-9	9-18	18-27
	.16	.16	.15
Tatchera sandy loam .. inch (Mallee) P, per cent	0-6	6-24	24-48
	.026	.017	.013

#### INSOLUBLE PHOSPHATIC FERTILIZERS

Phosphates insoluble in water may be used as fertilizers. These include rock phosphate itself, bone dust, and "basic super", the last-named being a mixture of super and lime in which the phosphate approximates to  $\text{CaHPO}_4$ . These fertilizers should be as finely ground as possible, in order to expose a maximum surface.

On the alkaline soils and in the dry climate of the wheat belt, no source of phosphate is as good as super. However, in the wetter climates of coastal regions, the less soluble compounds gain in two ways. They have more opportunity of coming into solution; and their phosphate cannot react quickly with iron and aluminium minerals, so may remain in a more available form on account of its combination with calcium. Basic super is deliberately prepared with the second



end in view. Even so it seems inferior to the separate application of lime and superphosphate. Bone dust is expensive as a phosphate fertilizer, and does not seem to have any special virtue, though it is of course a good thing that this by-product phosphorus should be returned to the land.

#### ESTIMATES OF AVAILABLE PHOSPHATE

The general arguments on p. 127 for the distribution of nutrients into first-, second-, and third-class supplies hold for phosphate. The extracting agents for estimating the higher classes of phosphate fall into two kinds. The first group consists of dilute acids, the best-known of which is Truog's solution<sup>2</sup>, dilute ammonium bisulphate at pH 3. The border line recommended by Truog is 45 parts of extractable phosphorus per million of soil if cereals are to be grown, and 75 parts for vegetables; below these levels, additional phosphate should be added. A common Victorian figure is 10 parts per million. The second group of reagents contain anions which are strongly adsorbed by sesquioxides; their use implies that the adsorbed phosphate which can be replaced by these anions can also be extracted by roots. These reagents include dilute alkali and ammonium fluoride. Citric acid belongs to both of these groups simultaneously.

#### *Rate of Reversion and Residual Effects:*

Soluble phosphate may disappear within an hour on some high-fixing soils. Other soils may retain soluble phosphate for weeks, and may retain the phosphate at a second-class level for years. Thus, many wheat soils of Western Australia were found to hold so much higher-grade phosphate after ten years of normal crop and fallow rotation that crops were reduced no more than 10 per cent by sowing without super during the period of rationing in 1941-5. We have deplorably little information as yet on the effect of the residual phosphate added to Australian soils during this century (see Table 33).

TABLE 33

BALANCE SHEETS OF PHOSPHORUS IN AN ACRE OF LAND	<i>Pounds</i>
Normal total in soil, 0-6 inch.....	500
Removed in 25-bushel wheat crop (0.24 per cent P).....	3.6
Annual removal in land so cropped once in 3 years.....	1.2
Removed in two fat lambs annually.....	0.8
Removed in 250 gals. milk and calves sold off dairy farm (cow to 2 acres).....	2.3
Loss in drainage water, 5 inches annually in Gippsland (0.2 p.p.m. or 1 lb. to 25 inches leaching rain).....	0.2
Annual restoration (1 cwt. super contains 11 lb.)	
(a) Gippsland, at least.....	11
(b) Wimmera, super added once in 3 years.....	4

<sup>2</sup> In the sugar-cane country of coastal Queensland, .01-normal H<sub>2</sub>SO<sub>4</sub> has been successfully used as an extractant to determine need for additional phosphorus.



## NATURAL PHOSPHORUS

The above discussion has centred on the fate of *applied* phosphate, since we rely so much on this for our first- and second-class supplies. The lower-grade reserves in the natural soil contain similar inorganic compounds to those discussed—namely, hydroxyapatite in alkaline soils, adsorption compounds of sesquioxides in acid soils. Primary crystalline apatite occurs only in a few exceptional immature soils. The inorganic phosphorus is almost all in the clay fraction. Organic compounds of phosphorus may make up one-third of the total supply of the surface soil. These have accumulated over the centuries from the residues of plants, fungi, and bacteria which have resisted attack by enzymes or by other micro-organisms. The phosphorus of these compounds is bound in ester form, and may be hydrolysed to give a metallic phosphate as in the equation—



where R is an organic group and M a metal. This hydrolysis is slow in soils—the more easily hydrolysed esters of plants having long since been destroyed—so that the great bulk of organic phosphorus is only a third-class source of the element to plants. However, even though it may be of little practical importance, it has been too much neglected by soil chemists up to date.

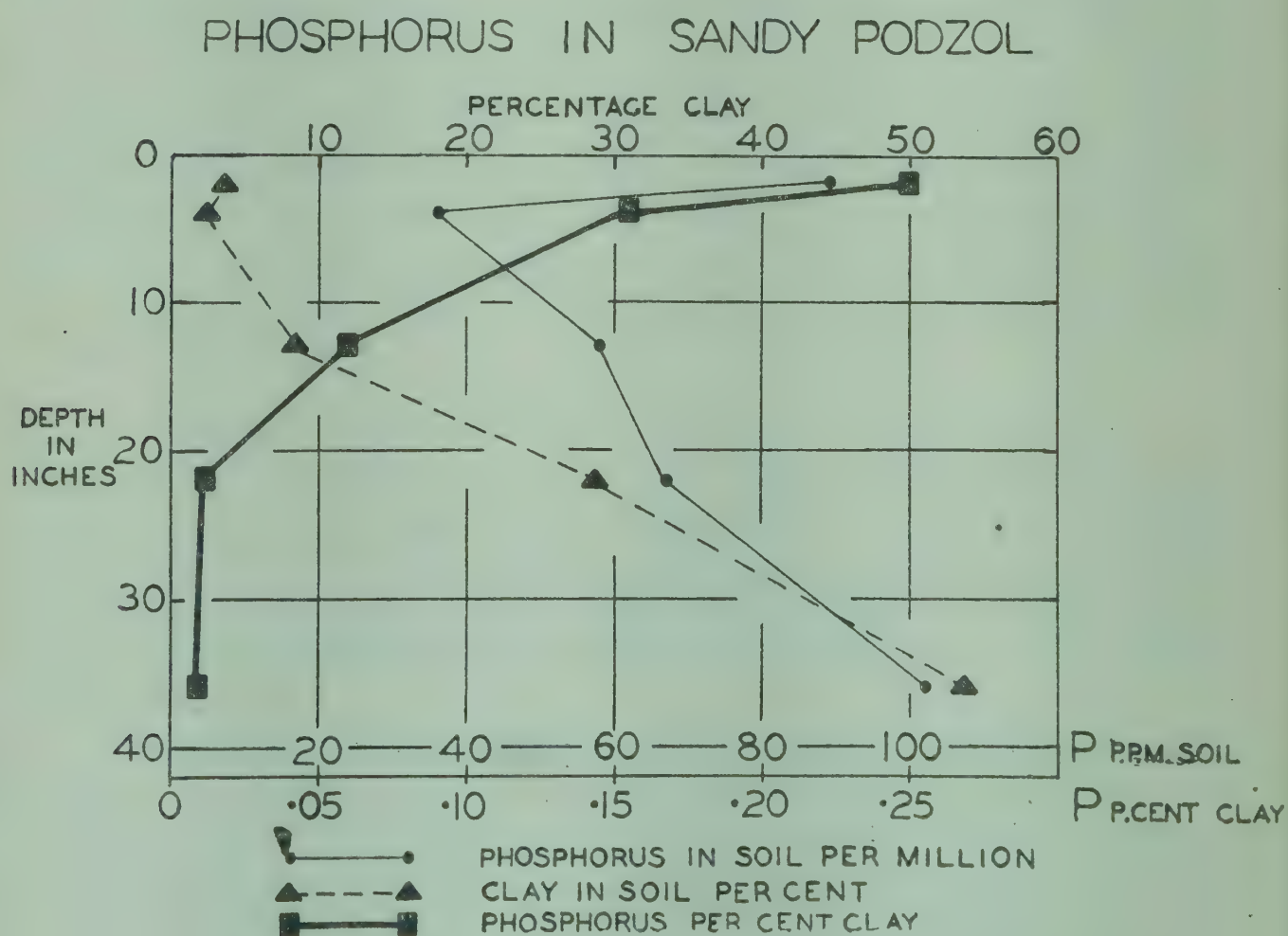


Fig. 36. Phosphorus in profile and its ratio to clay. (Lucaston sand, C.S.I.R. Bull. 92.)



*Phosphate in Subsoil*

As with other elements, relatively little attention has been given to the supplies of phosphate in the subsoil. As a rule the total amount diminishes with depth (Table 32), and the amount of available phosphate diminishes still more rapidly to traces only in the subsoil, though the deep subsoil may be richer if it rests on igneous rocks. This is another example of the work done by plants in bringing elements to the surface.

The ratio of phosphorus to clay is particularly interesting. This commonly amounts to between .05 and .25 per cent of the clay in the surface soil, and about one-tenth as much in the corresponding subsoil at two to three feet (see Fig. 36). A very heavy subsoil may contain as much total phosphorus as does the surface but the greater degree of saturation of the colloid with phosphorus in the surface emphasizes its higher availability there. The same principle shows that a sandy soil is probably better supplied with mobile phosphorus than is a heavy soil containing twice as much total supply.

The krasnozems of the east coast are extraordinarily high in total phosphorus. This phosphorus is extremely strongly held, and on that account has survived leaching by thousands of years of warm rain. On the other hand, the siliceous soils on the Pliocene and Pleistocene basalt of Victoria have lost over three-quarters of their original phosphorus under a much lighter rainfall.



## IRON, MANGANESE, ALUMINIUM, SILICON

THE MOST INTERESTING ASPECT OF THESE FOUR ELEMENTS IS THEIR DISTRIBUTION through the various horizons, which reflects the processes of soil formation (see Table 34 in appendix). They are all of biological importance also.

## IRON

*Plant Nutrition*

It is well known that plants and animals cannot live without iron. This knowledge, however, together with the recognition of iron in soil by red, brown, or yellow tints, has led to misunderstandings. A red soil does not provide abnormally high amounts of iron for the plants that grow on it. The very stability of the colour shows that the iron will not easily move. But whether there is "iron in the soil" in the popular sense of redness or not, there is nearly always ample iron in the plant. In spite of this, there are certain soils high in lime on which sensitive plants such as vines suffer through inability to carry this iron in their sap; the leaves become pale and *chlorotic*—that is, they fail to produce their normal supply of chlorophyll. Some peach trees growing on the "black" soil of the Wimmera show this chlorosis. Hydrangeas growing on heavily limed garden soils often show pale patches between the veins. Little is known of the reason for this physiological upset, but a spray or injection of an iron compound, ferrous sulphate or ferric citrate, usually cures it. Heavy applications of ferrous sulphate near the roots are often effective also. This seems curious, since the plant already contains ample iron. It appears that the new iron will also become immobile in the plant eventually, but the immobilization takes time and meanwhile the leaves are healthy for some weeks or months. Probably the iron is converted into insoluble ferric oxide within the plant. Acidifying the soil also cures iron chlorosis, but is usually too expensive to be practicable.

*Distribution in Profile*

Iron may be evident in the soil either as red or yellow tints permeating the whole mass or as concretions of 1 mm. upwards (generally known as "iron-stone"). Most red or brown soils owe their colour to *free ferric oxide*. This can be shown by extraction with acid oxalate solution or with a neutral sulphide solution followed by dilute oxalic acid. These reagents remove iron oxide<sup>1</sup> but

<sup>1</sup> Ferric oxide resists dilute acids such as hydrochloric, but reacts with organic reagents which form *complexes* with it—thus oxalate forms *ferrioxalate*, a green ion. Similarly, the complex-forming tendency of the thiocyanate ion brings enough iron into solution from acid soils to give Comber's test (p. 159).



hardly attack the rest of the clay, which they leave grey or brownish grey. A bacterial method of removal (see p. 199) is even simpler. Such free ferric oxide may make up ten per cent of the soil, but even 1-2 per cent can give a bright red, as in the soils of the Mallee. The yellow tints of many soils, however, are only slightly affected by such treatments; the iron is there as a yellow ferrisilicate and can only be removed by destroying the whole clay fraction. If the yellow is due to limonite ( $\text{Fe}_2\text{O}_3 \cdot \text{H}_2\text{O}$ ), which occurs especially in equatorial climates, then it is removed like the red anhydrous oxide.

Concretions rich in ferric oxide are common in soils which have been waterlogged (p. 44). In forming these the iron moves as ferrous ion, whether sideways or downwards. These concretions are resistant to weathering, but are probably being weathered in some profiles. In some places it is an open question whether the concretions are still being formed today, or are fully formed and now being weathered.

Iron is a constituent of the colloidal fraction, whether it is present as the free oxide or combined as a silicate analogous to the alumino-silicates. It is therefore commonly concentrated where colloid is concentrated, in B horizons of podzolic soils. This principle determines its distribution in most profiles.

#### MANGANESE

##### *Plant Nutrition*

The amount of manganese in plants varies with the soil to a greater extent than that of any other essential element. On acid soils a plant may contain over 1000 parts per million of dry matter; on alkaline soils the same species may contain only 10 parts. The supply is ample on all acid soils, except for some very poor leached sands; in fact the supply may be excessive—for example, tobacco growing on acid soils often suffers from manganese poisoning. At pH 6.5 or more, the intake is much less and may be deficient. Deficiency has been noted with many plants but is most acute with oats, and may cause a complete failure of the crop. In Australia this deficiency disease has occurred with oats and barley on a few characteristic soils; on naturally alkaline soil at Corny Point and Mount Gambier, South Australia, on poor gravelly sand in the southern wheat belt of Western Australia, and on a few properties on Bellarine Peninsula, Victoria, where lime has been applied to raise the pH to about 7.5. This last case has many parallels in Europe, where manganese deficiency has occurred on podzols that have been heavily limed.

##### *Chemistry in Soil*

The chemistry of manganese in the soil still has its obscure side, but this much is clear. Bacteria convert the bivalent ion to the insoluble oxides  $\text{Mn}_2\text{O}_3$  and  $\text{MnO}_2$ , gaining energy in the process; this oxidation is prevented by a pH



below 5, is relatively slow between pH 5 and 6, and is particularly vigorous from about pH 6.5 to 8. (These or similar bacteria have often blocked a town's water supply by depositing  $\text{MnO}_2$  in the pipes when the initial concentration in the water was 2 or 3 parts of Mn per million). These higher oxides can be reduced by organic compounds, especially in an acid environment, giving the soluble bivalent manganese again. As a result of these opposing reactions bivalent manganese can accumulate in toxic amounts in highly acid soils; it is present in sufficient but not dangerous amounts in slightly acid soils; and it falls to minute amounts in neutral and alkaline soils. The reason why manganese deficiency is confined to a very few soils of this last group is too complex to discuss further here.

Since the total manganese in the soil is nearly always ample, acidification with aluminium sulphate or with sulphur (which is quickly converted to sulphuric acid) prevents any deficiency disease. However, if the soil contains much free lime, this is not practicable, and then the choice is between a spray of  $\text{MnSO}_4$  over the affected plant or an application of  $\text{MnSO}_4$  with the seed. Two other treatments can only be applied in pots. One (which does not work with all soils) is to hold the soil under water for a month. The anaerobic bacteria then become active and use manganic and ferric oxides as a source of oxygen, releasing the bivalent ions. When drainage is restored, the manganese remains more available than before. The other treatment which is sometimes effective for a time is to sterilize the soil, either by heat or with a volatile antiseptic. This may work, both for manganese and for other major and minor elements, by abolishing microbial competition with the plant.

#### *Distribution in Profile*

In highly acid soils manganese may be leached out until very little remains. In other profiles, it accumulates at the surface (through the action of plants) and in alkaline horizons. The most interesting feature of manganese in the profile is the formation of manganiferous ironstone concretions in periodically waterlogged horizons. These may be a millimeter to a centimeter in diameter, and not very numerous; they may, however, contain practically all the manganese of that horizon. Apparently suitable conditions for bacterial colonies oxidizing ferrous and manganous ions are not easily found, and when one such colony is established it slowly grows, catching manganous ions as they diffuse by and fixing them as the higher oxide.

### ALUMINIUM

#### *In Plants*

Aluminium has already been discussed as a toxic element in acid soil (p. 163). It has been shown to be necessary for plants in minute amounts, but no plant



has yet been found to be suffering from aluminium deficiency in the field. One curious property of aluminium is its ability to convert the pink flower of the hydrangea to blue, as may be seen when a pink flower is sprayed with a dilute solution of aluminium citrate. It seems likely that the blue flowers which hydrangeas produce when growing on acid soils owe their colour to the high content of aluminium in the plant, though there are probably additional causes for the different colours produced on different soils.

### *Distribution in Profile*

This is often the same thing as the distribution of inorganic colloid, especially when dispersed clay has simply been washed vertically downwards (Tables 34, 35). However, iron, aluminium, and silicate may separate after they are set free by weathering, and the three may concentrate at different levels. Thus, the krasnozems of Gippsland become higher in aluminium and lower in iron with increasing depth.

## SILICON

### *In Plants*

Silicon like aluminium is said to be necessary in minute amounts, but a deficiency has never been found in the field. The monocotyledons absorb silicon in large amounts, so that half their ash may be  $\text{SiO}_2$ . The same plants in culture solution, however, seem to make similar growth, whether silicate is supplied or not. Little is known of the state of silicate in the soil solution. The simple ion  $\text{SiO}_3^{--}$  in solution aggregates through  $\text{Si}_2\text{O}_5^{--}$ ,  $\text{Si}_3\text{O}_7^{--}$ , etc., until it forms a particle of colloid size, but it is not known what limit there is to the size of a silicate particle that can enter the roots of a cereal.

### *Distribution in Profile*

While silicon is an essential part of clay, the total amount of silicon in any horizon is usually determined by the quartz, which remains as a sandy skeleton while colloids may be leached downwards. The amounts of silicon in some plants are so great that they may affect the distribution in the profile, but this possibility has never been studied. In equatorial climates the solubility of quartz is so high that it may be leached from the profile altogether.



## CHAPTER XVIII

### SULPHUR AND VARIOUS "TRACE" ELEMENTS

#### SULPHUR

SULPHUR AS SULPHATE, IS APPLIED TO THE SOIL NOT ONLY IN SUPERPHOSPHATE but also in ammonium sulphate. One hundredweight of superphosphate supplies 12 pounds of sulphur, whereas a 30-bushel crop of wheat removes only 3 pounds from an acre. Since the excess sulphate remains soluble in the soil and is hardly fixed at all by anionic exchange, the absence of any report of sulphur deficiency in Australia is not surprising. At the same time, some leafy crops remove fairly large quantities of sulphur, the cabbage with 30 lb. for a 25-ton crop being an extreme case. In some of the Western states of U.S.A., where superphosphate has not been used, sulphur and sulphates have increased the production of lucerne per acre by as much as 50 per cent. In wet climates, sulphur may also be lost in drainage in greater amounts than in crops sold off the land.

The sulphur cycle between the soil and the plant bears some analogies to the nitrogen cycle. Thus, sulphate ion is absorbed from the soil by the roots, and reduced in the plant to organic sulphur compounds; these compounds on the death of the plant become available as a source of energy to microbes, and microbial oxidation eventually leads back to sulphate.

The element sulphur has been locally applied to the soil in order to lower the pH (see p. 166).

#### "TRACE" ELEMENTS

The term "trace" or "minor" is given to elements needed by plants or animals in very small amounts (cf. pp. 123, 125). Each term has its advocates, but the use of "minor" is sometimes extended to include all elements other than the N, P, K, and Ca of the fertilizer trade. The trace elements needed by plants include copper, zinc, boron, and molybdenum besides those mentioned in Chapter XVII. Great precautions must be taken to prepare culture solutions free from the minute amounts of these needed for healthy growth. Copper, for example, should be kept at one part in ten million of solution to ensure the good growth of oats. This satisfaction with minute amounts makes it all the more curious that soils should fail to supply the needs of plants.

These elements furnish good examples of biological concentration (see Table 8, p. 47). The loss of surface soil by erosion may therefore involve a serious loss of minor elements. They are also relatively concentrated both in stable manure and in wood-ash.



### *Copper*

Copper deficiency is found on recent sand-dunes, consisting of shell-grit, formed on coasts exposed to the south-westerly wind, as at Robe in South Australia and Point Nepean in Victoria; and also on acidic peaty soils near Albany in Western Australia and on some poor sandy types both near the coast and further inland in Western Australia. A curious relation noticed in Western Australia is that subterranean clover fails in the absence of sufficient copper, however much superphosphate is added, and the inferior pasture plant, drooping-flowered clover, takes its place. Stock become unhealthy on pastures that are low in copper, and where the supply is just insufficient sheep while themselves healthy grow inferior wool without crimp, which is called "steely".

Copper is of peculiar interest since it is often deficient in country where the climate is good for crops or pastures, so that the discovery of its successful use is of great importance. As yet we know little about its state in the soil. Some very poor sandy or gravelly soils which need additional copper contain only minute total amounts of the element; as little as one pound of the metal per acre as  $\text{CuSO}_4$  may supply all that is needed for five years. Other soils, including the calcareous sand-dunes of Robe, precipitate copper completely, but even for these a quarter hundredweight per acre has lasting value.

### *Zinc*

Zinc salts have caused great increases in growth in two main kinds of country—firstly, on leached sand, as in some pine plantations in Western Australia, and secondly, on alkaline soils containing free calcium carbonate. In Victoria these include the mallee soils, on which both oranges and vines in the irrigated areas are greatly improved by sprays of  $\text{ZnSO}_4$ , and also the "black" soils of the Wimmera, where zinc salts mixed with the seed and the superphosphate often cause an increased growth of wheat.

### *Boron*

Boron deficiency has been recognized all over the world since about 1930. It is especially frequent and severe in beets and turnips, and in some districts a broadcast application of borax before sowing is essential in order to avoid a wholesale rotting of the roots. (Borax is highly poisonous, so must be applied only in small amounts at a time, 5 pounds an acre, and must not be mixed with the seed). These plants have a high requirement for boron, and a good crop may remove 80 gm. per acre; the small reserve of soluble boron in the soil (presumably borate,  $\text{BO}_2^-$ ) can thus be removed in a short time. The sea contains a remarkable amount of boron—one part in every thousand of total salt—and sediments laid down below the sea commonly contain a good reserve of the element.



### *Molybdenum*

Molybdenum is a surprising element to find among those essential to growth, but its importance has been established both in the purest culture solutions and in the field. Sodium molybdate ( $\text{Na}_2\text{MoO}_4$ ) at the rate of a pound an acre has given increased growth, especially of legumes, on poor ironstone country in the Adelaide hills and at Cressy in Tasmania. Molybdenum differs from all the other metals in being present not as a cation but as an anion,  $\text{MoO}_4^{--}$ . It is not precipitated in an alkaline environment like the cations of copper and zinc. On that account, the common method of purifying nutrient solutions of traces of heavy metals by shaking with  $\text{CaCO}_3$  does not work for molybdenum; it has to be removed by  $\text{H}_2\text{S}$ , which forms the insoluble  $\text{MoS}_2$ . This was a reason why it was not shown to be necessary until recently. It is probably essential for nitrogen fixation both by *Azotobacter* and by *Rhizobia*.

### *Cobalt*

Cobalt is not essential for plants, but it is for animals. In the absence of sufficient cobalt in the herbage, stock become anaemic. Cobalt deficiency of sheep, known as bush-sickness, was once acute in the pumice country of the North Island of New Zealand, but has been overcome by giving the animals a cobalt-containing lick. (It may also be dealt with by topdressing with cobalt sulphate, which has raised the cobalt content of the pastures from 0.1 to 0.6 part per million in one experimental field.) This deficiency was confined to land derived from two showers of volcanic ash—those from Taupo and from Kaharoa—which were particularly low in cobalt. Cobalt and copper are both deficient in some coastal districts of Australia, notably on the calcareous sand at Robe. The troubles of livestock associated with either deficiency are known as “coast disease”. Like copper, zinc, and manganese, cobalt becomes less available as the pH is raised.



## CHAPTER XIX

### SOIL EROSION

EROSION, IN THE GEOLOGICAL SENSE, IS ALWAYS GOING ON. RAIN RUNNING OFF a slope always carries some solids in suspension. Even without the help of rain, soil moves slowly down a hill; every time a particle is disturbed by the growth of a plant, by the fall of a tree, or by an animal, it slips down a little; this process is called "soil creep". Such normal erosion is very slow. While in time it wears the hills away, it is slow enough to allow mature soil profiles to develop.

Erosion may, however, be much faster than normal. This abnormal, accelerated erosion may strip the top few inches of the soil, or even the whole profile down to bedrock, in the course of fifty years or so. This is what we mean by the term "soil erosion". Soil may be thus eroded either by wind or by water. In either case man is usually to blame, through causing the soil to be left bare, whether by cultivation or by over-grazing.

#### WIND EROSION

Loss of soil by blowing is mostly confined to dry climates, as one would expect. There are two regions of serious wind erosion in Australia. The first is the pastoral semi-desert country on the dry side of the wheat belt, where the original cover of saltbush and other shrubs has been eaten bare by sheep and rabbits during droughts and has not recovered. The dust that is swept from this bare land is carried to the coast by the dry winds, and is sometimes brought down in coastal towns in the form of "red rain", particularly during the spring. Australian dust has even fallen with the rain in New Zealand. Though this erosion of the inland makes itself obvious to the city-dweller, it is less costly to the community than the erosion of the second region, the more valuable wheat-growing land of the Victorian and South Australian Mallee.

#### *Erosion in the Mallee*

Erosion in the Mallee consists mostly of the drifting of sand off cultivated land, covering fences, roads, and channels in its march. For the most part this moving sand is harmful, though some farmers claim that they have improved the texture of the heavier flats between the sandhills by ridging the land across the path of the drifting sand, so catching the sand and eventually mixing it with the rest of the soil. However, our main interest here is to consider what happens to the eroded profile. Most of the erosion occurs on sandhills, which must once have been moving dunes and were later fixed by vegetation, presumably under a less arid climate. They may have as much as six feet of sand,



overlying limestone rubble. If the cultivated and loosened layer, to a depth of three inches or so, is blown away, there is plenty of sand below, and crops may still be grown on the new surface, although the effect of previous additions of superphosphate is lost, together with small stores of minor elements and some of the organic matter which has to provide the nitrate. The damage becomes much more serious as the limestone layer is approached.

There has been a little drifting of the chernozem-like soil of the Wimmera. This is commonly prevented by leaving the surface rough. It is interesting to note that the eroded material consists of aggregates  $\frac{1}{4}$ - $\frac{1}{8}$  mm. in diameter—of about the same size as the drifting sand of the Mallee. While such crumbs give good structure for most purposes, they are just too small to resist the wind.

### *Methods of Control*

The control of erosion is a complex social problem; for example, it may be tackled by preventing the cultivation of certain sandy areas. All that can be considered in this section is, Given a wheat-growing property in the semi-arid south of Australia, what methods of management can prevent or minimize erosion?

The chief cause of wind erosion in the Mallee is the fine working of fallowed land. Now it is necessary to prepare the land for wheat by preventing the growth of weeds in the previous season, and so conserving water. But there is no merit in frequent and fine cultivation, such as was advised when the doctrine of upward capillary movement held the field. Instead, the surface is left as cloddy as possible during the dry season by working when the land is as wet as possible. A rough surface also breaks the wind, which does damage only when it sweeps over a long smooth surface. Though this cloddy surface is easily formed on the calcareous clay of the Wimmera, it may hardly be possible on a Mallee sand.

The working of the land may even be avoided altogether by using sheep to keep down the weeds. Such a "sheeped fallow" results in a slightly lower yield of wheat in the following season but greatly reduces erosion. The same principle is used when a thin cover-crop of oats is sown in August and is eaten down by sheep, leaving enough residue to protect the soil through the hot weather. This reduces erosion to practically nothing.

### EROSION BY WATER

This is commonly divided into two classes, sheet erosion and gully erosion. These two forms commonly occur together.

*Sheet erosion* by water, as by wind, means the removal of a few inches of soil over large patches of land. It may happen when water flows over bare land without concentrating into any one channel. The effect is often brought about



on ploughed land; if a number of small channels are scoured out of the loose soil and the whole surface is later made smooth again by cultivation, eventually the loss is distributed over the whole area. This may happen so slowly that the farmer does not notice anything for many years, until patches of yellow subsoil show, as in some of the apple orchards on the steeper slopes of the hills to the east of Melbourne.

*Gully erosion* (Plate XI) is the result of concentrating the flow into one channel. In many cases this may have started as a natural watercourse. The eroded gully differs from the normal watercourse in having steep, bare sides, and in being deep out of all proportion to the water that it carries. Once formed, it is likely to work backwards and develop tributaries up the hill, through the continual slumping of the soft subsoil.

Slope, climate, soil, and the use of the land are all concerned in determining the degree of erosion by water. The effect of slope is simple. The risk of erosion increases rapidly with steepness; a slope of 1 in 10 is dangerous for cultivation, whatever precautions are taken, and with still steeper slopes it is inadvisable to clear the land at all, the limit here depending on the particular climate and management. The other factors are dealt with below.

### *Climate*

The worst water-erosion in Australia following settlement is on the inland slopes of the Great Dividing Range in New South Wales and Victoria—that is, where a hot, dry season regularly alternates with a wet season, and the total rainfall is considerable—20 inches or more. It is the same in other parts of the world. Some of the worst cases of erosion are found in the countries bordering the Mediterranean Sea, where a dry summer alternates with a wet winter. In all these places, if vegetation is eaten up by stock during the long drought, there is nothing to protect the soil from the first severe rain. It is significant that the worst example of water-erosion in southern Victoria is in its driest and hottest part, namely near Bacchus Marsh. But the same kind of climate favours erosion in agricultural land. Where land is bare-fallowed, it is open to erosion by summer thunderstorms; much of the sloping wheat land in New South Wales has been badly eroded in this way, as also have a few areas in Victoria, such as Dookie.

The intensity of rainfall is also important. A thunderstorm falling in summer or autumn and bringing 50 points in half an hour will do more damage than a whole winter's rain, since it must all run off rapidly. The greater the risk of intense falls, the greater the risk of erosion. While we have no exact figures, we know that this risk increases as we go north and east from the Western District of Victoria into northern New South Wales. In the far north of Australia,



where a long dry season breaks with violent thunderstorms in summer even natural erosion is so severe that soil has not developed over much of the hilly country.

An interesting example of the importance of climate is the dairying land of Apollo Bay. In spite of the very steep slopes and the wet climate, these hills are not eroded. Droughts are unknown, the grass is green all the year round, and there are no bare patches exposed to the rain.

### *Nature of the Soil*

Some soils erode more easily than others in the same climate. The factors concerned here are complex. One would suppose at first that permeability was the best property, since the more rapidly the rain is absorbed the less flows over the surface and so the less soil is carried with it. However, sandy soils, though permeable, are also easily eroded since they are not coherent enough. Some of the most resistant soils are tropical krasnozems, which are highly ferruginous, permeable and yet coherent. Some of the most easily eroded soils are those with a permeable surface overlying an impermeable clay at six inches; the surface may then easily become sodden and be converted into a semi-liquid mass. This may happen with structureless, easily dispersed types. A loose layer of tilled soil overlying a compact seedbed is similarly sensitive.

### *Nature of Cover*

This is of overwhelming importance. The mechanical action of beating raindrops in dispersing the soil is the most serious single cause of erosion. A eucalypt does little to stop this beating; but grass, or any dense cover, stops it completely, and allows the water instead to soak in gently. Roots certainly play some part in holding the soil together, but that part is small compared with that of leaves close to the surface.

### *Damage done by Erosion*

If sheet erosion has reached to bedrock or to a stony layer, so much land has clearly been lost. Usually, however, a few inches of surface soil are removed, leaving either a thin A horizon or a B horizon for succeeding crops to grow on. The yield of crops is commonly much lower on this new soil. To some extent this is due to the loss of the supplies of nutrients in surface layers. However, even if the deficient elements are supplied, the yield is still usually low. When this is so, the reason is the poor physical structure of the subsoil. The yellow B horizon of many podzolic types is compact and high in clay and poorly aerated. If organic matter could be incorporated with it, it would be greatly improved in structure. The main problem in reclaiming such exposed B horizons seems



to be to get anything at all to grow on them for ten years or so; once they have been permeated by roots, they should be able to support a fair growth with the aid of fertilizers. Subsoils are not necessarily poor. The best example of the successful use of subsoil is in the crabholey land of the Wimmera. When this was levelled for cultivation or irrigation, the surface of the puffs was scraped off, leaving exposed subsoil. Yet there is no sign today of any unevenness due to this treatment. Where the land was put under irrigated pasture, all sign of unevenness had disappeared within three years.

The damage done by gulying is of a different kind. The total amount of land lost in a gully may not be serious (though the existence of a gully indicates that there is probably sheet erosion also). However, the gully makes parts of the property inaccessible; it acts as a drain and so lowers the productivity of the low-lying areas during the dry season; and it delivers water at a great rate to lower levels.

Besides the damage described, erosion increases the high run-off of rain which originally caused it. Thus the process is cumulative. The hills are parched still more severely in the dry season, and the lower slopes have to deal with still more water in the wet season.

All this relates to the damage done on the farm. At the same time, there is the damage done to the community, with water-erosion as with wind-erosion. A gully may destroy a road or a bridge. More important, the rapid run-off from eroded land may make the flooding of rivers more severe and more frequent. Again, the eroded material must be deposited somewhere. It may fill up a reservoir, as has happened in many parts of U.S.A.; or it may cover a rich river flat; the coarse sand deposited on flats as at Bruthen and Orbost in recent years has lowered their fertility. To avoid all these losses, the remedy must be applied at the source—on the farm itself or in the forest.

#### *Methods of Treatment*

There are various devices for dealing with gullies by blocking the rush of water and forcing it to drop its load of suspended matter, so eventually filling in the bed. However, prevention is better than cure. The first object should be to keep the water on the hills as long as possible, and allow it to soak away slowly. The simplest example of treatment is the contour furrow on grassland. A series of shallow furrows are cut along the contour at a distance of twenty or thirty feet from one another. Though they are only a few inches deep, they can hold up the rain-water long enough to give it a chance to soak in. These furrows have two excellent effects. Firstly, more water is held on the hill, so more feed is produced there than ever before. Secondly, much less water reaches the lower slopes, and formerly active gullies there cease to flow in wet weather, are



gradually grassed over and may eventually be filled in from the sides. If land is continually overgrazed, of course, this device will not succeed.

On agricultural land, a similar principle is applied—namely, ploughing along the contour (actually with a minute downward slope) instead of straight up and down the hill. Again, a rough surface holds up the water better than a finely-worked one. Besides this technique, the land may be managed differently. If the alternating crop-and-fallow system is stopped for a few years and the land left under grass, the soil is improved in structure and is thus more resistant to erosion when next cropped. Recent American work on the protective effect of plant residues on the surface is also important. These experiments with wide-spaced crops such as maize and sorghum have shown that erosion is negligible and yields are improved if the land has been prepared with a subsoil plough which cuts roots and loosens the soil without turning in the residues. Such experiments follow naturally on the recognition since about 1932 that the old belief in turning the soil upside-down had no real basis.



## APPENDIX

### NOTE ON CHEMICAL TERMS

THE READER IS ASSUMED TO BE FAMILIAR WITH THE IONIC CONSTITUTION OF SALTS, with the use of the term pH, and with the nature of buffering. Unfortunately, archaic usages have lingered in soil science long past their time. Thus, the double-oxide theory of salts—the doctrine of Berzelius in 1820, that magnesium sulphate is  $\text{MgO} \cdot \text{SO}_3$ —persists in two fields. Firstly, many writers still record elements as their oxides<sup>1</sup>; calcium appears not as the simple element, but as  $\text{CaO}$  (which does not exist in soil) and phosphate appears as  $\text{P}_2\text{O}_5$ , which is quaintly referred to as “phosphoric acid”. The phosphate radicle ( $\text{PO}_4$ ), which does exist, should surely be preferred, or alternatively the element (P), which many Americans have already adopted. These can be converted into one another on the basis 1.00 part of P is equivalent to 2.29  $\text{P}_2\text{O}_5$  and to 3.06  $\text{PO}_4$ .

The other relic of the double-oxide theory is the term “base exchange”, which is still often used instead of *cation exchange*. This deplorable term “base exchange” has caused untold confusion. The cations which take part in exchange reactions include calcium, magnesium, ammonium, and hydrogen. Of these, hydrogen is the essence of acidity, and it is the height of absurdity to call it a “base”. Ammonium is a weak acid, by virtue of its tendency to liberate hydrogen ion ( $\text{NH}_4^+ \rightleftharpoons \text{NH}_3 + \text{H}^+$ ), so its salt ammonium chloride is acid to methyl red. The ions of the metals calcium and magnesium, though one could hardly call them acids, are most certainly not bases. A base is something which reacts with or removes acid—that is, hydrogen ion; it would be interesting to learn from the champions of the term “base exchange” what interactions  $\text{Ca}^{++}$  and  $\text{H}^+$  have with one another. This fallacy comes from the days when it was the *bases*  $\text{CaO}$  and  $\text{MgO}$  that were exchanged, as compared with the *ions*  $\text{Ca}^{++}$  and  $\text{Mg}^{++}$  of to-day.

Lastly, while it is outside the scope of this book to discuss the way in which plants deal with nutrient elements, it must be emphasized that the roots absorb these elements as ions, and not as molecules. Chemists have become so used to writing formulae like  $\text{KNO}_3$  and  $\text{MgSO}_4$  for solid salts that some of them imagine that these molecules exist as such, both in the solid state and in solution. It is very doubtful whether these molecules exist at all, even in strong solutions; but we need not trouble about that problem here, since they certainly do not exist in the dilute solutions in which roots live. The root is surrounded by a solution containing  $\text{K}^+$ ,  $\text{Ca}^{++}$ ,  $\text{Mg}^{++}$ ,  $\text{Na}^+$ ,  $\text{NO}_3^-$ ,  $\text{H}_2\text{PO}_4^-$ ,  $\text{SO}_4^{--}$ , and many other ions. It cannot tell whether the potassium ion which it is just absorbing

<sup>1</sup> Oxides are used in Table 34 in order to check the total of 100%.



was once paired with a nitrate ion or a chloride; such information is useless in any case. The root absorbs the positive and negative ions independently, presumably at different points, and probably by exchange reactions, excreting hydrogen in exchange for potassium and possibly bicarbonate for nitrate.

#### TOTAL ANALYSIS OF SOILS

Boiling HCl only dissolves part of the finer fractions from soils. For total analysis, a soil must be fused with  $\text{Na}_2\text{CO}_3$  in platinum—a much more formidable job. Total analyses have not been published in Australia, but many figures are available in America. Such figures, while of no immediate practical value, are essential for the study of soil formation.

Table 34 shows the total analysis of a profile of Fox silt loam. This is a “grey-brown podzolic” soil developed from glacial dolomitic till on level,

TABLE 34  
TOTAL ANALYSIS OF FOX SILT LOAM  
(U.S. DEP. AG. TECH. BULL. 834)

Depth inches	Horizon	pH	%Clay	$\text{SiO}_2$	$\text{Fe}_2\text{O}_3$	$\text{Al}_2\text{O}_3$	MgO	CaO	$\text{K}_2\text{O}$
0-2	A1	6.6	12.7	69.0	2.9	7.8	0.6	1.2	1.8
2-10	A2	5.4	16.0	78.8	3.5	8.8	0.6	0.4	1.9
10-18	A3	4.6	14.9	79.4	3.4	9.2	0.6	0.3	1.9
18-32	B2*	4.6	28.3	73.5	5.7	12.5	1.0	0.4	1.9
32-38	B3	6.7	47.1	62.9	8.2	16.2	2.0	1.1	2.1
38-60	C1	8.1	2.9	41.3	2.4	4.6	8.2	17.9	0.9

Depth inches	$\text{Na}_2\text{O}$	$\text{TiO}_2$	MnO	$\text{P}_2\text{O}_5$	$\text{SO}_3$	Igni- tion loss	TOTAL	Organic
0- 2	0.8	0.6	0.17	0.16	0.08	14.6	99.7	12.3
2-10	0.9	0.7	0.15	0.13	0.02	3.6	99.5	2.3
10-18	0.9	0.7	0.14	0.11	0.02	2.9	99.6	1.0
18-32	0.9	0.7	0.09	0.11	0.01	3.4	100.2	0.4
32-38	0.8	0.6	0.19	0.18	0.02	5.9	100.2	1.1
38-60	1.5	0.2	0.09	0.06	0.02	22.8	99.8	0.4



high-lying ground in Indiana. The A horizon, separated into three layers, is a silt loam changing with depth from grey to yellowish-brown. The B horizon, where clay has accumulated, is yellowish-brown to dark brown, and becomes heavier with depth. This passes abruptly into the alkaline parent material at 3 to 4 feet. (The high loss on ignition of this lowest horizon is due to decomposition of  $\text{CaCO}_3$ ).

Most of the profile is markedly acid, only the lower B horizon at 3 feet showing some effect from the neighbouring limestone. Evidently a great depth of limestone has dissolved away to yield the residues from which the surface 3 feet are derived.

The main chemical features are:

- (1) Si is very high in surface, still high but decreasing in lower horizons.
  - (2) Al, Fe, and Mg increase with depth to the lowest B horizon.
  - (3) K is steady throughout the profile.
  - (4) Ca and P fall from a maximum at the surface to a minimum in the second foot.
- The changes of Si, Al, Fe, and Mg, however, merely reflect the washing of clay into the subsoil. Quartz, and therefore silicon, remain more concentrated in the surface, while the Al, Fe, and Mg make up part of the clay anion. Ca and P are concentrated at the surface by plants, while K is partly so concentrated and partly moves downwards with the clay. These relations are brought out in Table 35, where the various elements are re-calculated as percentages of the clay fraction of less than 2 microns. Analyses of other leached soils give similar results to those shown here, including the low fertility of the subsoil clay.

TABLE 35

SOME CONSTITUENTS OF FOX SILT LOAM AS PERCENTAGES OF CLAY  
FRACTION IN EACH HORIZON

Depth inches	Horizon	$\text{Fe}_2\text{O}_3$	$\text{Al}_2\text{O}_3$	MgO	CaO	$\text{K}_2\text{O}$	MnO	$\text{P}_2\text{O}_5$
0-2	A1	22	61	5.1	10.0	14.4	1.3	1.2
2-10	A2	22	55	3.7	2.4	12.1	0.9	0.8
10-18	A3	25	61	3.9	1.7	13.0	0.9	0.7
18-32	B2*	20	44	3.6	1.4	6.5	0.3	0.4
32-38	B3	18	35	4.3	2.2	4.5	0.4	0.4
38-60	C1	79	153	282	616	31	3.1	2.1

\*The absence of a B1 horizon is curious. Presumably this horizon (18-32 in.) was named B2 because it resembled the B2 horizons of other grey-brown podzolic profiles in which B1 was also present.



## SUGGESTIONS FOR PRACTICE

Since one purpose of this book is to provide information for teachers, some suggestions for experiments and demonstrations are put forward here.

*Microbial Action*

The following two simple preparations allow us to observe microbial action without a microscope. They are in the tradition of the experiments in Hugh Nicol's book, *Microbes by the Million*, in the Pelican series, from which other ideas may be gained.

(a) *Manganiferous concretions*—Soil is well mixed with 3 parts of a 1½ per cent solution of agar, which must be cooled to about 40°C before mixing. This is poured into a petri dish and allowed to set. A central plug of the jelly is removed by digging with the open end of a test tube, and a solution of agar containing 1 per cent manganous sulphate is poured in to fill the hole. The dish is covered to prevent evaporation, and left in a warm place (or in an incubating oven, if one is available). In time dark brown deposits of manganic oxide form on the soil-agar mixture. These are of microbial origin, and are not formed if an antiseptic is present. The time needed for developments varies from two days to a month, mixtures of pH close to 7 being the quickest to form the deposit. Below pH 5 the manganic oxide is not produced. Such microbial oxidation is responsible for the large amounts of manganic oxide found in some concretions, especially those consisting largely of ferric oxide.

(b) *Anaerobic reactions*—Anaerobic organisms can be studied in 200 cc. bottles, into which first soil and then water is added so that each bottle is nearly full, with half an inch of water standing above the saturated soil. The bottles are tightly corked and left in a warm place (an ordinary room will do during the warmer months).

The visible sign of anaerobic activity is the destruction of any red tint and the appearance of black streaks of ferrous sulphide, especially in the lower parts of the bottle. When the stopper is removed, a characteristic smell is noticed, and a ferric precipitate develops where the ferrous solution, formed while the bottle was closed, comes in contact with oxygen. If an infertile podzolic subsoil is used for this experiment, it can be used to show the need for both calcium and a source of carbon before ferrous sulphide forms, the untreated soil being compared with bottles containing half a gram of  $\text{Ca(OH)}_2$  or a few grams of chopped straw or both together.

(Albrecht, Soil Sci. 51.213).

*Selective Extraction of Free Ferric Oxide*

This may be extracted either chemically or biologically.

(a) *Chemical method*. This consists of boiling the soil with a solution of sodium



sulphide brought to pH 7. This forms ferrous sulphide and sulphur; the ferrous sulphide is extracted with dilute acid, and the sulphur can be extracted from the dried soil with carbon bisulphide. The treatment also dissolves small amounts of aluminium and silicon from the colloid. Some soils need a preliminary dispersing treatment as for mechanical analysis.

(*Method* by Truog et al., Soil Sci. Soc. America **1**, 108. Results reported for various Australian soils in study of colour by Beck, J. C.S.I.R. **12**, 128. Other figures for Victoria, *Proc. Roy. Soc. Vic.* **55**, 10, and Tasmania, C.S.I.R. *Bull.* 108. See Piper's *Soil and Plant Analysis* for detailed discussion of methods.)

(b) *Biological method*. The soil is covered with a solution of sucrose (1 part sucrose to 20 soil) in an erlenmeyer flask. The flask is corked, and an outlet tube runs through the cork with its other end dipping into a trough of water, so excluding air and providing a safety-valve for the gases evolved. The apparatus is incubated at 25° until all trace of red has disappeared. Additional calcium may be desirable as  $\text{Ca}(\text{OH})_2$ . The supernatant solution containing ferrous salts can finally be blown out with  $\text{CO}_2$  and analysed, and the soil recovered after treating with  $\text{H}_2\text{O}_2$ . Only traces of aluminium and silicon are removed by this method. (Allison and Scarseth, *J. Am. Soc. Agronomy*, 1942. 616).

#### Colorimetric Determination of pH

The difficulty about using an indicator to measure the pH of a soil is that the soil becomes turbid with water. One arrangement for overcoming this is to soak a sample of soil with indicator solution until some of the indicator filters through the mud. Another way is to add a flocculating agent. The only reagent that is used is barium sulphate (X-ray standard), a suspension of which is positively charged and so flocculates mutually with the negative clay, while its effect on the pH is slight. The soil is shaken in a test-tube with an equal volume of barium sulphate and excess water, together with  $\frac{1}{2}$ -1 ml. of an indicator solution. The colour of the indicator is read after settling (5 minutes). A universal indicator (a mixture of three or four individual indicators), covering the range from 4 to 9, should first be used, and if desired a more accurate figure obtained by choosing the individual indicator that changes colour at about the soil's pH. Colour standards for this purpose are usually obtainable commercially.

This method is at least correct to .4 of a pH unit, and is usually better than this. It may give low results for alkaline soils, since atmospheric  $\text{CO}_2$  can attack the unbuffered solutions in which the colour is observed.

The following indicators are most useful:

		<i>pH Range</i>
Brom thymol blue	.. ..	6.0-7.6
Brom cresol purple	.. ..	5.2-6.6
Brom cresol green	.. ..	3.8-5.4



*Staining Tests*

The capacity of a soil to adsorb the ions of fertilizers may be shown approximately by its ability to remove organic dyes from solution, thereby becoming stained itself. In the following test, derived from Lundblad (Soil Science, vol. 41, p. 391) methylene blue is used as a coloured cation, and sodium alizarin sulphonate ("Alizarin S") as a coloured anion. They thus symbolize potassium and phosphate respectively.

Weigh out 1 gm. of finely-ground soil in a test-tube, add 10 ml. of 0.1 per cent solution of methylene blue in water, cork and shake vigorously. If the solution on settling is colourless or only a light blue, add more methylene blue, 1 ml. of 1 per cent solution at a time. Continue, shaking and standing overnight, until the solution remains intensely coloured. Calculate the amount of methylene blue absorbed per gram of soil estimating colorimetrically the amount remaining in solution.

Follow the same procedure simultaneously using a solution of Alizarin S. (This is also an indicator of pH, but this does not affect the experiment). The relative adsorbing power for methylene blue compared with alizarin S is high for siliceous colloids, low for sesquioxidic colloids. Alizarin S resembles phosphate in being strongly held by krasnozems.

*Chromatography*

Chromatograms are useful for demonstrating the competition between different ions for adsorption on an oppositely charged surface. Prepare about 50 gm.  $\text{Al}_2\text{O}_3$  by adding NaOH to a hot strong solution of alum or  $\text{AlCl}_3$ , filtering and then heating the precipitate to dull red heat. Grind and take the fraction from 100-200 mesh, make it into a paste with water, and prepare a column of solid by pouring through a length of  $\frac{3}{4}$ -inch glass tubing packed at the base with glass wool and passing into a pressure flask, using suction.

This  $\text{Al}_2\text{O}_3$  is prepared for adsorbing cations by adding a ml. of dilute NaOH and drawing this through under suction, next washing out the excess with water. The particles now are negatively charged and hold exchangeable  $\text{Na}^+$  on their surface. Add 1 ml. of a mixture of two-thirds molar  $\text{CuSO}_4$  and  $\text{CoSO}_4$  and apply slight suction. The Cu is adsorbed first and the Co below it, giving a banded column or chromatogram. This can be washed white with dilute acid and restored by treating first with alkali and water, then with the coloured metal solution.

For anions, finer  $\text{Al}_2\text{O}_3$  (below 200 mesh) works better. This is packed as above and then prepared by sucking through first dilute  $\text{HNO}_3$ , then water. The particles are now positively charged and hold exchangeable  $\text{NO}_3^-$  on their surface. Add a mixture of saturated  $\text{KMnO}_4$  and  $\frac{\text{M}}{2} \text{K}_2\text{CrO}_4$  and apply slight



suction. The  $\text{CrO}_4^{--}$  is adsorbed first, and the  $\text{MnO}_4^-$  below it;  $\text{MnO}_4^-$  is held very feebly and is easily washed out with water.

### *Rapid Approximate Determination of Organic Matter*

Place a weighed sample of half a gram of finely ground soil into a dry erlenmeyer flask, add 10 ml. of 0.4N  $\text{K}_2\text{Cr}_2\text{O}_7$  followed by 10 ml. of concentrated  $\text{H}_2\text{SO}_4$ . Place funnel in neck to act as condenser, heat to boiling-point and keep just simmering for 10 minutes. When cool, dilute with a large bulk of water and titrate the excess dichromate with standardized  $\text{FeSO}_4$ . Hence calculate the amount of dichromate reduced by the organic matter. Tiurin, who devised this method, used the figure that one ml. of normal oxidizing solution was equivalent to 3.30 mg. organic carbon, or 5.7 mg. organic matter.

As an alternative, add 10 ml. of N  $\text{K}_2\text{Cr}_2\text{O}_7$  and 20 ml. of  $\text{H}_2\text{SO}_4$  and let the reaction take place at the resultant temperature ( $110-120^\circ$ ) without further heating. For this method a milliliter of normal oxidizing agent is equivalent to about 3.8 mg. organic carbon.

For soils containing more than 4 per cent organic matter the above amounts of chromic-sulphuric mixtures should be doubled or further increased, keeping always the equal volumes of dichromate solution and sulphuric acid.

A still more rapid and rough estimate of organic matter is by colorimetry. The sample of soil is first freed of lime or exchangeable calcium by washing with dilute HCl, followed by water. It is then shaken with bench-reagent ammonia, and the depth of colour of the extract is taken to be proportional to the amount of organic matter present. Two soil extracts can thus be compared with each other colorimetrically. The dark brown to black material extracted by the ammonia is a bacterial by-product and resembles many complex organic compounds in being deeply coloured in alkaline solution and only slightly coloured in acids.

### *Structure Analysis*

A cylinder about 4 inches in diameter and 16 inches high is fitted so that it can be filled with water from below and emptied by a rapid siphon as soon as the level reaches about 3 inches from the top. A set of sieves, ranging from 4 mm. to  $\frac{1}{4}$  mm. in mesh, is made to fit closely together, and the topmost 4 mm. sieve is fitted with lugs enabling it to hang from the top of the cylinder. There should be at least three sieves, of 4, 1, and  $\frac{1}{4}$  mm. mesh, but more intermediate sizes could also be used. The soil is taken moist from the field, and a sample of 20-25 gm. weighed out on the top sieve, which should hang so that the water just covers the soil before the siphon starts to work. The tap is turned on, and the apparatus kept running until the outflowing water is clear (about 20 minutes). The stable aggregates remaining on the sieves are dried and weighed. This



method without further refinement shows the difference between soils of good and bad structure. Further details are given by Downes and Leeper, *Proc. Roy. Soc. Vic.*, **52**, 4-8.

A similar result may be gained by putting the weighed sample of soil on the topmost sieve, and dipping the whole set of sieves several times into a bucket of water.

*Indirect Measurement of  $pF$  from 2.5 to 5.0*

This method is used only on the "fine earth". Samples of about 100 gm. of soil are well mixed with various amounts of water in the range between air-dry and sticky-point. Half of the moistened sample is placed in a 10 cm. petri dish and a filter-paper (Whatman 542) laid over it; the other half of the soil is placed on top, taking care to make the best possible contact between soil and paper. The petri dish is covered and kept for five or six days in a closed vessel at an even temperature. The filter-paper is then placed in a weighing-bottle after shaking off any soil that can be quickly removed; the bottle plus paper is weighed and dried to constant weight at  $105^{\circ}$ . At the same time a sample of the moist soil is taken and dried at  $105^{\circ}$ . From these weighings one calculates the percentage of water in the paper and in the soil, both in terms of the oven-dry solid. The moist soil was thus in equilibrium with paper of a certain percentage of water. If the paper has itself been calibrated for  $pF$ , the  $pF$  of the moist soil can now be written down.

The calibration of the paper is taken from the work of Gardner (*Soil Sci.* **43**, 277) who first suggested this method. He states that filter papers differ little. The following figures can be used to reconstruct his graph for reference :

% water in paper	..	113	53	37	25	14	11	4
$pF$	..	2.5	3.5	4.0	4.5	5.0	5.5	6.0

The paper should be protected from fungal attack. This is done by dipping into dilute mercuric chloride solution and then drying. The dried paper is then ready for the experiment.

*Determination of  $pF$  curve from 1.0 to 2.0*

(Leamer and Shaw, *J. Am. Soc. Agronomy* **33**, 1003)

This part of the curve is determined on soil in a state as close as possible to that of the field. It thus differs from the drier part of the curve, for which "fine earth" is used. The sample is taken in the field in a cylinder of 1-inch to 3-inch diameter and about 3 inches deep. A piece of cheesecloth is fastened over the bottom with a rubber band. The soil is not allowed to dry, but



is wetted from below by being placed in an outer vessel containing water at a level just below that of the soil. After surplus water has drained away under gravity, the sample is ready for the experiment.

The apparatus is designed to submit several samples at the same time to a tension of between 10 cm. and 100 cm. of water (pF 1 to 2). This requires (a) a shallow trough of water which is kept continually under the required tension, and (b) a layer of absorbent material in contact with the water, on which the soil samples can stand while being drained. For (a), a sheet of glass about 8 inches square is fitted with a shallow metal trough, and let into a table or shelf at about shoulder height. A hole is made in the centre of the sheet, and a rubber tube is connected which leads to a reservoir of water, which can be held at any desired level below that of the trough. (b) Wire gauze is laid over the central opening of the glass sheet, and then a sheet of blotting paper above it, to fit the sides of the metal trough. The water stands over the part of the glass sheet that is covered by the wire; otherwise, if the blotting-paper lay directly on the glass, it would be drier away from the centre and so would transmit different tensions to the soil above. The blotting-paper is covered with a thin layer of silt, prepared by decantation and carefully freed from any clay. The silt, consisting of particles less than .02 mm. with correspondingly small pores between them, ensures that when the tension is applied no air can be drawn through to upset the experiment. The soil cylinders, fitted with muslin at the base, are placed on this silt layer, above the wire gauze. They are covered to prevent evaporation and are weighed initially and after draining at selected tensions up to 100 cm. They are then dried and the percentage of water held at each tension is determined. The final figures can be in terms of weight or volume.

The following device is used by Leamer and Shaw under (a) to be sure that the silt remains wet. A 200 cc. bottle is clamped at the desired level below the silt. The rubber tube running from below the glass sheet joins a glass tube which runs to the bottom of this bottle. A small stream of water dripping through a capillary tip into the same bottle from a conveniently placed carboy constantly replenishes the supply, and a capillary siphon also leaves the bottle, the outside arm of which is shorter than the inside, so that the level of water in the bottle will not drop below the level of the outside arm.

#### *Tensiometer*

See Baver, *Soil Physics*, p. 206.

#### *Mechanical Analysis*

The fractions are determined by using Stokes's formula, which describes the rate ( $v$ ) at which a small sphere falls through a liquid

$$v = \frac{2}{9} gr^2 \frac{d_1 - d_2}{\eta}$$



where  $r$  is the radius,  $\eta$  the viscosity,  $d_1$  the density of the solid and  $d_2$  the density of the liquid. The viscosity of water at  $20^\circ$  is 0.01, and the density of the soil particles is taken as 2.6. The equation then becomes approximately  $v = 35,000 r^2$ . Using this equation, the largest particle of the clay fraction (.002 mm. diameter) falls 10 cm. in 8 hours, and the largest particle of the silt fraction (.02 mm.) falls 100 times as fast or 10 cm. in 4 minutes 48 seconds. For most purposes this can be taken as 5 minutes; the exact time for any temperature is given in books such as Piper's *Soil and Plant Analysis*.

If a sample of 10 gm. or 20 gm. of soil is weighed out, the sand fractions (above .02 mm.) can easily be separated by decantation. The soil is dispersed by rubbing with NaOH in a beaker and water is added to reach a level of 10 cm. After 5 minutes the liquid is poured away. Water is again added to the 10 cm. level, the residue is stirred up and this liquid also poured off after settling for 5 minutes. After five or six decantations the liquid that is poured away is clear and only sand remains in the beaker. This is dried and separated into coarse and fine fractions with a sieve.

The same principle of dispersion and settling is used for separating the smaller fractions. Silt can be separated during a week by decanting every evening (10 cm. in 8 hours) and clay estimated by difference. (In the routine method, an aliquot sample of clay suspension is taken by a pipette at a depth of 10 cm. after 8 hours, or more easily in a cylinder at 25 cm. after 20 hours, and this sample is evaporated and weighed when dry.) In estimating clay by difference, organic matter and water in the air-dry soil must be allowed for.

One of the most tedious parts of the routine method is the preliminary dispersion. Soils high in organic matter have to be treated with  $H_2O_2$ , and some calcareous soils have to be washed with HCl before they will disperse in alkali. Many soils, however, can be simply dispersed by two hours of mechanical shaking of the fine earth (10 or 20 gm.) with about 200 ml. of water containing 5 ml. of normal NaOH and 5 ml. of saturated  $Na_2C_2O_4$ . These include the red-brown earths, many podzolic surfaces, and the majority of subsoils.

#### *Hydrometer Short-cut*

If the soil has been well dispersed, the finest particles can be estimated with very little labour by using a sensitive hydrometer, which responds to slight differences in the amount of solid in suspension and which is stream-lined so as not to disturb the suspension when inserted.

A tall cylinder of suspension is prepared and shaken, and the hydrometer inserted and read after half a minute standing and after several hours. The method is described in *Public Roads*, vol. 14, p. 193. It has been used especially by road engineers, for example the Country Roads Board in Victoria.



*Soil Profile Models*

The object is to produce a permanent record of the profile as it would be seen in the side of a trench or quarry. The model consists of actual soil from the different horizons on a backing of stout 3-ply. A convenient size is 18 by 3 inches, and the scale should be one-fourth of natural size. Setting aside  $2\frac{1}{2}$  inches for a label at the bottom and a margin on top, this allows the uppermost 5 feet of the profile to be represented on the model.

The board is first painted with a dark grey paint so that any cracks forming later are not conspicuous. The soil is then stuck with glue, the boundaries of each horizon being first drawn on the board.

*Gravel*—Any gravel is shown in actual size, covering the surface allotted to its horizon in proportion to the *weight* of the gravel in the sample. The gravel is ground flat on one surface before sticking, and is attached to the board before the fine earth is added.

*Fine earth*—This is ground to pass a 1 mm. sieve, and any coarse sand of 1-2 mm. added to the bulk. It is sprinkled on the glue surface (see next paragraph) from a glass tube or bottle, one end of which carries a cork with a hole of about  $\frac{3}{4}$ -inch diameter with a disc of 2 mm. sieve covering the hole. Each horizon has its own sprinkler, but when two horizons merge into each other in the field they should be made to do so in the model, either by mixing beforehand or by thinning out and then overlaying with the second horizon. About 4 grams of soil is needed per inch of horizon, more being needed for sandy soils.

*Glue*—Fairly dilute water-soluble glue is the best sticking agent; it must be dilute enough for soil to sink in. It is applied hot and thick with a brush and the soil shaken on quickly, and spread smoothly with a dry brush until all the damp spots are covered. The soil should be pressed lightly into the glue with a flat spatula if it does not sink in readily, and in any case the surface should be made smooth.

When the glue has set to a jelly, the margins are trimmed. The margin should be about half an inch at the top end and half an inch down one side, for carrying information such as pH and texture (or clay content).

The next morning the glue has set hard and the surplus soil is shaken off. Water is now applied with a brush until the soil on the 3-ply is saturated and the junctions of horizons are smoothed over. If the gravel has been covered with soil it can be scraped clean at this stage. On drying a second time, heavy horizons crack but sandy ones do not. This re-wetting provides an opportunity for depicting mottling; if streaks or blotches of different colours occur in a horizon, the differently coloured parts should be picked out and applied as a paint on top of the main layer of soil. Alternatively, these streaks may be applied as chalk after the model has dried, especially streaks of soft lime.



The following points may also prove useful.

Sometimes when the soil dries it may curl away from the backing, in which case more concentrated glue can be run under it and the soil pressed back to the board and held there till it dries.

The 3-ply tends to buckle as the glue dries. To get over this the 3-ply is nailed by means of  $\frac{1}{2}$ -inch headless nails to a firm piece of wood. This has a raised strip of wood running down the left side, and the left side of the 3-ply strip is pressed up against the raised strip before nailing in position. Four nails only are needed—one in each top corner, one in the middle of the strip and one at the bottom. These can be pulled right through the 3-ply when it is dry. The raised portion on the left prevents the glue flowing over that edge. The right side has the  $\frac{1}{2}$ -inch margin, and this is trimmed off with the top margin when the glue is still in the jelly stage.

The glue tends to run under the left side of the 3-ply and make it stick to the frame. To prevent this a few thicknesses of newspaper can be placed under the 3-ply and over the raised strip before the 3-ply is nailed in position. Even if this sticks to the 3-ply it can easily be scraped off after the glue is dry. It is essential that the 3-ply should not be taken off the frame until the glue is dry, otherwise it may warp.



## BIBLIOGRAPHY

## (a) GENERAL

If the reader wishes to follow the study of soils further, the following books should be useful. Comber's *Introduction to the Scientific Study of the Soil* (Arnold) has already been mentioned as the best introductory book published overseas. Brade-Birks, *Good Soil* (English Universities Press) is a good popular book. A more advanced general treatment is given by Sir John Russell in *Soil Conditions and Plant Growth* (Longmans Green), the most famous of English textbooks. The Yearbook for 1938 of the U.S.A. Department of Agriculture, *Soils and Men*, contains much valuable and readable information. On a rather more technical level, the following books are recommended for their particular aspects of the subject.

G. R. Clarke, *The Study of the Soil in the Field* (Oxford Univ. Press).

A small book dealing entirely with profile study, and surprising the reader with the number of detailed properties which an enthusiast can detect (e.g. the seven kinds of mottling!).

L. D. Baver, *Soil Physics* (John Wiley). An outstanding book, especially for the treatment of structure.

G. W. Robinson, *Soils. Their Origin, Constitution, and Classification* (Murby). Deals mainly with systematic classification.

H. Jenny, *Factors of Soil Formation* (McGraw Hill).

C. S. Piper, *Soil and Plant Analysis* (Hassell Press, Adelaide). A valuable collection of analytical methods.

While the discussion of the campaign against fertilizers which goes on under various names (*organic farming*, *biodynamics*) is outside the scope of this book, the reader is referred to *Chemicals, Humus, and the Soil*, by D. P. Hopkins (Faber and Faber). This book sets out the scientist's point of view lucidly and with considerable understatement.

However good textbooks may be, a thorough student keeps in touch with the living science only through the technical journals. The best of these are American; *Soil Science* (monthly) and *Proceedings of Soil Science Society of America* (annual), both of which are taken by several Australian libraries. *Chemical Abstracts* is a thorough and well-indexed abstracting journal with which to start a search for information on some special topic, including many that are not strictly chemical.

## (b) AUSTRALIAN

The only published summary of information on Australian soils is Professor J. A. Prescott's pamphlet *The Soils of Australia*, published in 1931 as *Bulletin* 52 of the Council for Scientific and Industrial Research (C.S.I.R.). The map appears in revised form as *Bulletin* 177 in 1944. Other modern summaries are of Tasmania by C. G. Stephens (C.S.I.R. *Bull.* 139) and of Western Australia by L. H. J. Teakle (*J. Roy. Soc. W.A.* 24, 123). Other work is scattered in bulletins and numerous journals; the following are the most important.

*Soil Surveys*. Various *Bulletins* of C.S.I.R.; other Victorian work is referred to on p. 13.



*Irrigation, Drainage, and Salt.* C.S.I.R. *Bulletins* 74, 128, 149 and *Pamphlet* 113; also various soil surveys, e.g. Kerang, *Bulletin* 125.

*Descriptions of Soil Groups in Australia.* Properties of Red Loams, Red-brown Earths, Mallee soils, and Black earths (Chernozem-like) in *Trans. Roy. Soc. S.A.*, Vols. 60, 62, 56 and 59 respectively. Red Loams of N. Tasmania, C.S.I.R. *Bull.* 108; of New South Wales in N.S.W. Dep. Ag., *Regional Soil Series*, Nos. 1 and 2.

There are many journals which contain articles dealing with soils. For the most part, Universities publish in the journals of the Royal Societies in each state. The work of C.S.I.R. is published in its own journal, or in bulletins. Each state department of agriculture has its own journal which may contain an occasional technical article, but only that of Western Australia carries much important matter, notably a series between 1940 and 1944 on minor elements, especially copper. Queensland now publishes in addition the Queensland Journal of Agricultural Science and the Victorian Department of Agriculture has a new series of Technical Bulletins.

In New Zealand most of the work of value is published in the New Zealand Journal of Science and Technology.

*Soil Structure.* The local information is taken from an article by R. G. Downes and G. W. Leeper, *Proc. Roy. Soc. Vic.* 52, 1-20.

*Minerals of the fine sand.* Local work by A. Nicholls, *Proc. Roy. Soc. Vic.* 49, 17 and *J. Aust. Inst. Ag. Sci.* 5, 218. E. R. Graham's work is in *Soil Sci. Soc. America*, 6, 259.

*Minerals of colloids.* A few samples by Hosking, *J.C.S.I.R.* 13, 206.

*Nitrogen.* On the nitrogen cycle as affecting southern Australia, the most comprehensive work is that of the Waite Institute (*J. Ag. Sci.* 1930, 517: *Empire J. Exp. Agric.* 1, 193, 325). In Victoria, articles on ley farming at Rutherglen give some information (*J. Dep. Ag. Vic.* 1940, 1943, 1947-8).

*Declining fertility* under rotations of cereal cropping and fallow at Victorian experimental stations, see H. C. Forster, *J. Dep. Ag. Vic.* 1939, p. 130.

*Phosphate fixation* in Victorian soils by M. R. Lawry, *Proc. Roy. Soc. Vic.* 55, 1-12.

*Wilting point*, direct determination, Marshall and Williams, *J. Aust. Inst. Ag. Sci.* 8, 109-111.

*Soil Erosion in Victoria* (Victorian Lands Dept.) contains a collection of articles on the subject together with illustrations.

Very little work on soils has been published in Victoria, apart from the books and articles already mentioned.



## SYSTEMATIC NAMES OF PLANTS

Barley grass	..	..	Hordeum maritimum
Belar	..	..	Casuarina lepidophloia
Blackwood	..	..	Acacia melanoxylon
Bluebush	..	..	Kochia sp.
Blue Gum	..	..	Eucalyptus globulus
Buckshorn plantain	..	..	Plantago coronopus
Buloke	..	..	Casuarina lepidophloia
Burr medick	..	..	Medicago denticulata
Button grass	..	..	Gymnoschoenus sphaerocephalus
Chickweed	..	..	Stellaria media
Dillonbush	..	..	Nitraria Schoberi
Drooping-flowered clover	..	..	Trifolium cernuum
Fat hen	..	..	Chenopodium album
Fog grass	..	..	Holcus lanatus
Grass-tree	..	..	Xanthorrhoea australis
Heath	..	..	Epacris impressa
Honeysuckle	..	..	Banksia marginata
Hopbush	..	..	Dodonaea attenuata
Ironbark	..	..	Eucalyptus sideroxylon
Jarrah	..	..	Eucalyptus marginata
Kauri	..	..	Agathis australis
Mallee	..	..	Eucalyptus dumosa, E. oleosa, etc.
Manna gum	..	..	Eucalyptus viminalis
Messmate	..	..	Eucalyptus obliqua
Mountain grey gum	..	..	Eucalyptus goniocalyx
Murray pine	..	..	Callitris glauca
Peppermint	..	..	Eucalyptus radiata
Red gum	..	..	Eucalyptus rostrata
Red stringybark	..	..	Eucalyptus macrorrhynca
Saltbush	..	..	Atriplex spp.
Samphire	..	..	Salicornia australis
Sandalwood	..	..	Myoporum platycarpum
Shore thistle	..	..	Carduus pycnocephalus
Snow gum	..	..	Eucalyptus pauciflora
Sorrel	..	..	Rumex acetosella
Stringybark	..	..	Eucalyptus capitellata
Subterranean clover	..	..	Trifolium subterraneum
Sundews	..	..	Drosera spp.
Swamp tea-tree	..	..	Melaleuca ericifolia
Tussock grass	..	..	Poa caespitosa
Variegated thistle	..	..	Carduus Marianus
Wallaby grass	..	..	Danthonia spp.
White gum	..	..	Eucalyptus viminalis
Wimmera rye-grass	..	..	Lolium rigidum
Yorkshire fog	..	..	Holcus lanatus



LIST OF PLACE-NAMES (Fig. 37)



Fig. 37. Places referred to in the book.

			District	No.
Anglesea .. ..	..	..	Central .. ..	45
Apollo Bay .. ..	..	..	Western .. ..	41
Bacchus Marsh .. ..	..	..	Central .. ..	43
Bamawm .. ..	..	..	Northern .. ..	15
Barrabool .. ..	..	..	Central .. ..	46
Bellarine Peninsula .. ..	..	..	Central .. ..	48
Benalla .. ..	..	..	North-east .. ..	27
Berwick .. ..	..	..	Central .. ..	51
Birregurra .. ..	..	..	Western .. ..	39
Bogong High Plains .. ..	..	..	North-east .. ..	24
Broadford .. ..	..	..	North-central .. ..	21
Bruthen .. ..	..	..	Gippsland .. ..	69
Carlisle River .. ..	..	..	Western .. ..	40
Camperdown .. ..	..	..	Western .. ..	36
Cohuna .. ..	..	..	Northern .. ..	13
Coragulac (Warrions) .. ..	..	..	Western .. ..	38
Cranbourne .. ..	..	..	Central .. ..	52
Cressy .. ..	..	..	Western .. ..	30
Dalmore .. ..	..	..	Central .. ..	53



Dargo High Plains	..	..	Gippsland	..	..	65
Darnum	..	..	Gippsland	..	..	58
Dookie	..	..	Northern	..	..	18
Euroa	..	..	North-east	..	..	25
Glenorchy	..	..	Wimmera	..	..	11
Goulburn Valley	..	..	Northern	..	..	★
Hamilton	..	..	Western	..	..	29
Hopetoun	..	..	Mallee	..	..	7
Inverloch	..	..	Gippsland	..	..	60
Katamatite	..	..	Northern	..	..	14
Kerang	..	..	Northern	..	..	12
Kinglake	..	..	Central	..	..	42
Kooweerup	..	..	Central	..	..	54
Koroit	..	..	Western	..	..	35
Lake Corangamite	..	..	Western	..	..	33
Lake Murdeduke	..	..	Western	..	..	32
Lindenow	..	..	Gippsland	..	..	64
Longerenong	..	..	Wimmera	..	..	9
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Murrayville	..	..	Mallee	..	..	5
Myrtleford	..	..	North-east	..	..	26
Natimuk	..	..	Wimmera	..	..	8
Natte Yallock	..	..	Northern	..	..	19
Newry	..	..	Gippsland	..	..	62
Nilma	..	..	Gippsland	..	..	57
Nyora	..	..	Central	..	..	55
Omeo	..	..	North-east	..	..	28
Orbost	..	..	Gippsland	..	..	70
Ouyen	..	..	Mallee	..	..	3
Point Nepean	..	..	Central	..	..	49
Rupanyup	..	..	Wimmera	..	..	10
Rutherglen	..	..	North-east	..	..	23
Sale	..	..	Gippsland	..	..	66
Shepparton	..	..	Northern	..	..	16
Swan Hill	..	..	Mallee	..	..	6
Tarwin	..	..	Gippsland	..	..	61

★“Goulburn Valley” commonly denotes a broad band running north-west from Shepparton and Tatura to the Murray.

★★Moira is the furthest eastern portion of the Northern District.



Tatura	..	..	..	Northern	..	..	17
Terang	..	..	..	Western	..	..	34
Trentham	..	..	..	North-central	..	..	20
Walpeup	..	..	..	Mallee	..	..	4
Warragul	..	..	..	Gippsland	..	..	6
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